Next Meeting, November 25, 1904, Chapter Room, Carnegie Hall, New York.
Subject: Heavy Electric Traction.

Entered as matter of the second class at the New York, N. Y. Post Office, Nov. 20th, 1890.

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TRANSACTIONS

OF THE

AMERICAN INSTITUTE

OF

ELECTRICAL ENGINEERS.

CONTENTS.

FOR TABLE OF CONTENTS SEE FIRST PAGE.

PUBLISHED MONTHLY (EXCEPTING JULY AND AUGUST) BY THE INSTITUTE, UNDER THE SUPERVISION OF THE EDITING COMMITTEE.

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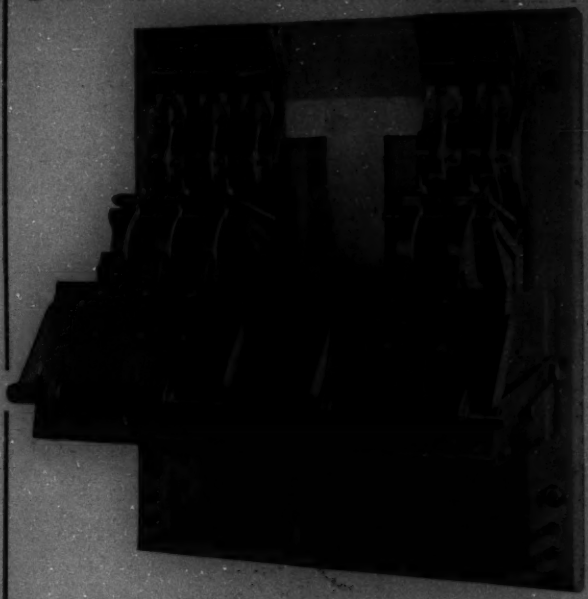

I-T-E Remote Control Switches for Equalizer Circuits

Where equalizer leads are run from the generator to the switchboard and back through a considerable distance, not only are the series field circuits given unduly high resistance, but in addition to this the cost of the copper cables becomes excessive. While these conditions render obvious the desirability of having the equalizer switches located close to the generators, at the same time it is also evident that these switches must be under the immediate control of the switchboard attendant.

We illustrate herewith a pair of equalizer switches which we have designed and developed to meet these conditions. The right-hand switch is of 2000 amperes, the left-hand of 3000 amperes capacity. The upper terminal of each connects with the equalizer main, which takes the place of the equalizer bus otherwise required at the switchboard.

The closing and opening of the switches is effected from the switchboard by the movement of a small double throw switch.

THE CUTTER CO.

PHILADELPHIA

Circuit Breaker Engineers and Manufacturers

TRANSACTIONS

OF THE

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

Vol. XXI. NOVEMBER, 1904. No. 9

TABLE OF CONTENTS.

SECTION I.

Notice of Discontinuance of Monthly Announcements iii
Officers and Board of Directors, 1904–1905 iv
Committees and Local Secretaries v
November meeting of the INSTITUTE vi
Dates and Subjects of Future Meetings vi
Applications for Election vi
Applications for Transfer vii
Branches and Student Meetings vii
Students of the INSTITUTE x
Branches: Chairmen, Secretaries, and when Branches Meet xii
General Society Items relating to the Joint Meeting of the AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS and the Institution of Electrical Engineers of Great Britain, held at Festival Hall, World's Fair Grounds, St. Louis, Mo., Wednesday, September 14, 1904 xiii
Associates Elected, October 28, 1904 xvi

SECTION II.

The Transposition of Electrical Conductors, by Frank F. Fowle 789
Discussion at St. Louis, Sept. 14, 1904, on "Different Methods and Systems of Using Alternating Current in Electric Railway Motors," by President Arnold, Chas. P. Steinmetz, B. G. Lamme, Professor Perry, President Gray, C. V. Drysdale, Frank J. Sprague, Elihu Thomson, ... 818
Advertisements 839

SECTION I.

GENERAL INSTITUTE MATTERS.

This section contains INSTITUTE matters of general interest formerly printed in the Monthly Announcement. Being of a temporary nature these items will not be printed in the bound volumes. In future the bound volumes will contain only matters that are intended for permanent record—reports of committees, technical papers, discussions on these papers, and written communications relating to them.

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D. B. RUSHMORE, Pittsfield, Mass.

NEXT MEETING, NOVEMBER 25, 1904.

HEAVY ELECTRIC TRACTION.

1. *Factors Influencing Subway Motor Specifications*, by LEWIS B. STILLWELL, Member; Electrical Director, Interborough Rapid Transit Co., New York.

2. *Problems on Electric Traction on the Long Island Railroad*, by O. S. LYFORD, JR., Associate; Electrical Engineer, Westinghouse, Church, Kerr & Co., New York.

PLACE OF MEETING.

CHAPTER ROOM, CARNEGIE HALL,
154 West 57th Street, New York.

FUTURE MEETINGS.

December 23,

TRANSMISSION PROBLEMS.

The Maximum Distance to which Power can be Economically Transmitted, by RALPH D. MERSHON, Member; Consulting Electrical Engineer, New York and Montreal.

January 27, 1905,

CENTRAL STATIONS.

February 24, 1905,

TRANSPORTATION.

APPLICATIONS FOR ELECTION.

Applications have been received by the Secretary from the following candidates for election to the INSTITUTE as Associates, and will be considered by the Board of Directors at a future meeting.

Any Member of Associate objecting to the election of any of these candidates should so inform the Secretary before December 23, 1904.

4161 L. Frank Kohler,	New York City.
4162 William C. Forsythe,	Tallahassee, Fla.
4163 Pierre V. C. See,	Chicago, Ill.
4164 August J. Pahl,	San Francisco, Cal.
4165 William M. Talbott,	Havana, Cuba.
4166 Frederick S. Stitt,	New York City.
4167 John S. Cowgill,	Three Rivers, Mich.

4168	James Heywood,	Philadelphia, Pa.
4169	John S. Henderson, Jr.,	Wilkinsburg, Pa.
4170	Hans C. R. P. Specht,	Wilkinsburg, Pa.
4171	Domingo L. Monjo,	Elizabeth, N. J.
4172	Yoshio Shirojo,	Tokyo, Japan.
4173	Homer McCullough,	Sheridan, Mont.
4174	Eldin S. Moulden,	Chicago, Ill.
4175	Walter Wood,	Philadelphia, Pa.
4176	Robert J. Browne,	Calcutta, India.
4177	Orville H. Ensign,	Los Angeles, Cal.
4178	Adolph Shane,	Ames, Iowa.
4179	Roscoe Woltz,	Lynn, Mass.
4180	John R. Williams,	Birmingham, Ala.
4181	Norman Rowe,	Guanajuato, Mexico.
4182	Henry W. Peck,	Pittsburg, Pa.
4183	James Kent,	Boston, Mass.
4184	Charles S. Hamner,	Schenectady, N. Y.
4185	Charles V. Allen,	E. Orange, N. J.
4186	Henry A. Pressey,	Washington, D. C.
4187	Fred H. Kroger,	Boulder, Colo.
4188	Alexander S. Spiegel,	Chicago, Ill.
4189	Francis P. Foster,	Corning, N. Y.

Total, 29.

APPLICATIONS FOR TRANSFER FROM ASSOCIATE TO FULL MEMBERSHIP. FIRST READING.

Recommended for transfer by Board of Examiners, Oct. 12, 1904.

Arthur Clarke Eastwood, Engineer, The Electric Controller and Supply Co., Cleveland, O.

William Amzi Dick, Designing Electrical Engineer, Westinghouse Electric and Mfg. Co., Pittsburg, Pa.

Edward Jerome Cook, Chief Engineer, Cleveland Electric Railway Co., Cleveland, O.

BRANCHES AND STUDENT MEETINGS.

Since the distribution of the October Transactions, several Branches have reported that they have held meetings for the purpose of organizing and outlining Branch activity during the Institute year 1904–1905. Some Branches have elected and installed new officers, and some have appointed new committees

for arranging and carrying out the Branch work. The principal changes reported are the following:

IOWA STATE COLLEGE BRANCH.

Meeting held October 12, 1904.

Professor B. S. Lanphear, Secretary of this Branch, died, after a brief illness, at his home in Carthage, N. Y., on Friday, October 14, 1904. M. P. Cleghorn is now Acting Secretary of this Branch.

PENNSYLVANIA STATE COLLEGE BRANCH.

Meeting held September 28, 1904.

G. L. Christman, *President.* H. L. Frederick, *Secretary.*

Vice-presidents.

W. M. Seguine. C. E. Govier.

W. E. Kaiser, *Marshall.*

Social Committee.

C. L. Eshleman. T. H. Arnold. C. O. Bennett.

The junior members of the Pennsylvania State College Branch gave a dinner to the society on Saturday evening, October 8. More than 50 members were present. Among the toasts were: "Our New Members," P. M. Rainey; "Our History," Professor J. P. Jackson; "Social Meetings," C. L. Eshleman; "Esprit de Corps," Dr. R. E. Myers; "Wanderings," A. R. Dennington. The toastmaster was J. C. Christman.

Another meeting was held by this Branch on October 19, 1904.

PHILADELPHIA BRANCH.

The 13th meeting of the Philadelphia Branch was held on Monday, October 10, at the rooms of the Engineers' Club. an interesting paper on "Wireless Telegraphy" was presented by C. D. Ehret. The paper covered the ground of wireless telegraphy, historically and technically. There was a short discussion in which Messrs. W. C. L. Eglin, McClellan, and Braddell took part. The members were then taken under charge of Mr. J. W. Kelley, Jr., to visit the plant of the Keystone Telephone Company at Second and Sansom streets. Through the efforts of Mr. Kelley, Mr. Ulrich, the traffic manager of the company, and their assistants, the visit was very interesting; the meeting did not break up until midnight.

PITTSBURG BRANCH.

Meeting held October 17, 1904.

Norman W. Storer, *Chairman*. S. M. Kintner, *Secretary*.

EXECUTIVE COMMITTEE.

P. M. Lincoln. H. W. Fisher. Norman C. McPherson.

PITTSFIELD BRANCH.

A meeting of the Pittsfield Branch was held Oct. 28, 1904, 25 members and guests being present. The chairman gave a short sketch on the INSTITUTE history, the development of the local Branches, and of the progress which they were making. Also, a suggested outline of the work for the coming year, which may include a discussion of the INSTITUTE papers, original contributions by local members and addresses by prominent engineers. The papers presented at this meeting were those from the TRANSACTIONS of the INSTITUTE, which were read at the Chicago meeting, June 21, 1904. F. V. Nicholls opened the discussion by contrasting the switching arrangements necessary for long power-transmission systems and those for large power-houses in the great cities. J. J. Kline contributed information with regard to the operation of the California transmission systems. G. G. Ponti told of the parallel operations of transmission lines in northern Italy and described some lightning-arresters used there. Geo. Carter described the circuit interrupter. A. W. Pierce and Mr. Wilson contributed to the discussion on ground shields for transformers. Announcement was made that the next meeting would be on November 11 and that Mr. Gilbert Wright would present an original contribution on the subject of "Power-House Design," with especial regard to the large power houses in New York City.

UNIVERSITY OF MISSOURI BRANCH.

Meeting held September 30, 1904.

H. B. Shaw, *Chairman*. Wray Dudley, *Secretary*.

EXECUTIVE BOARD.

H. B. Shaw. Wray Dudley. J. E. Buckham.
E. M. Maddox. L. C. Coleman.

Another meeting of this Branch was held on October 14, 1904.

TORONTO BRANCH.

Meeting held October 28, 1904.

The executive committee of this Branch is considering the advisability of holding two meetings instead of one meeting every month.

UNIVERSITY OF WISCONSIN BRANCH.

Meeting held October 26, 1904.

J. P. Mallett, *Chairman.* G. C. Shaad, *Secretary.*

EXECUTIVE COMMITTEE.

J. P. Mallett. G. C. Shaad. F. W. Huels.

STUDENTS OF THE INSTITUTE.

At a meeting of the Board of Directors, March 27, 1903, the privilege of enrolling as a Student of the AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS was granted to any student regularly pursuing electrical studies. Applications for Student enrolment are now promptly acted upon, provided they are made in strict compliance with the following By-laws:

Sec. 55. *A person pursuing a regular course of study in electrical subjects, may be enrolled as a "Student of the American Institute of Electrical Engineers," as herein provided.*

Sec. 56. *A person desiring to be enrolled as a student shall make a written application upon a form provided for that purpose, which application shall be endorsed by a Member or Associate of the Institute.*

Sec. 57. *A fee of* $3.00, *covering one year, must be paid in advance for this privilege. Upon receipt of this fee, the applicant's name may be placed upon the mailing list, subject to the approval of the Board of Examiners and the Board of Directors. The privileges of enrolment as a Student may be continued for three years, provided at the expiration of each year the fee of* $3.00 *for the following year be paid within* 30 *days after presentation of the bill for that year.*

Sec. 58. *Applicants who have received engineering degrees are not eligible for enrolment as Students, unless their applications were filed before graduation.*

Sec. 59. A person who is regularly pursuing electrical studies, but who is not a graduate of a technical college or school, may be enrolled as a Student as herein provided.

Sec. 60. Students enrolled under the provisions of these By-laws shall each be entitled to receive regular monthly PROCEEDINGS *and ordinary notices of meetings. They will be permitted to purchase single bound volumes of the* TRANSACTIONS *at $3.50 each.*

Between March 27, 1903, and October 27, 1904, 466 Students have enrolled and remained in good standing.

The advantages of the Student relationship to young men in college was admirably presented in the letter of Professor H. J. Ryan of Cornell University, printed in the October TRANSACTIONS. Professor Ryan has shown an active interest in the matter by sending in a list of 84 students (with remittance of $252.00) who were duly enrolled on October 24.

Some of the schools and colleges from which applications for Student enrolment have been received are as follows:

Cornell	118
Purdue	83
Iowa State	77
Pennsylvania State	35
Armour Institute of Technology	34
Missouri	25
Ohio State	20
Michigan	14
Lehigh	13
Worcester Polytechnic	13
Colorado	13
Syracuse	13
Minnesota	13
Stanford	12
Union	11
Wisconsin	11
Illinois	9
Stevens	7
Georgia Technology	7
Clarkson Memorial Technology	7
Washington University	6
Harvard	2

Branches and Date Started.	Chairman.	Secretary.	When Branch Meets.
1 **Chicago** 1893	George A. Damon.	Peter Junkersfeld.	
2 **Minnesota** ..... Apr. 7, '02	George D. Shepardson.	E. P. Burch.	Friday after New York meeting.
3 **Pittsburg** ..... Oct. 13, '02	Norman W. Storer.	S. M. Kintner.	
4 **Cornell University** Oct. 15, '02	Harris J. Ryan.	Geo. S. Macomber.	2d and 4th Tuesdays.
5 **Lehigh University** .. Oct. 15, '02	Wm. S. Franklin.	William Esty.	3d Thursday
6 **Univ. of Wisconsin** Oct. 15, '02	J. P. Mallett.	George C. Shaad.	Every Thursday.
7 **Univ. of Illinois** ... Nov. 25, '02	W. H. Williams.	Morgan Brooks.	
8 **Denver** ..... Dec. 8, '02	Henry L. Doherty.	Eugene Y. Sayer.	
9 **Cincinnati** ..... Dec. 17, '02	B. A. Behrend.	Louis E. Bogen.	
10 **Ohio State Univ.** .... Dec. 20, '02	W. R. Work.	S. B. Williams.	
11 **Penn. State College** Dec. 20, '02	C. L. Christman.	H. L. Frederick.	Every Wednesday
12 **Univ. of Missouri** .. Jan. 10, '03	H. B. Shaw.	W. E. Dudley.	1st Friday.
13 **St. Louis** ..... Jan. 14, '03	W. E. Goldsborough.	Gerard Swope.	2d Wednesday.
14 **Purdue University** . Jan. 26, '03	W. E. Goldsborough.	J. W. Esterline.	
15 **Schenectady** ..... Jan. 26, '03	C. P. Steinmetz.	R. Neil Williams.	
16 **Philadelphia** ..... Feb. 18, '03	H. A. Foster.	H. F. Sanville.	2d Monday.
17 **Boston** ..... Feb. 13, '03	C. L. Edgar.	C. B. Burleigh.	1st Wednesday.
18 **Iowa State College** . Apr. 15, '03	L. B. Spinney.	M. P. Cleghorn.	1st Wednesday.
19 **Washington, D. C.** .. Apr. 9, '03	Samuel Reber.	Philander Betts.	1st Thursday.
20 **Toronto** ..... Sept. 30, '03	T. R. Rosebrugh.	R. T. MacKeen.	2d Friday.
21 **Columbus** ..... Dec. 20, '03	L. G. White.	M. C. Hull.	2d & 4th Mondays
22 **Seattle** ..... Jan. 19, '04	R. G. Dunn.	W. V. Sullivan, Jr.	2d Saturday.
23 **Atlanta** ..... Jan. 19, '04	A. M. Schoen.	W. R. Collier.	
24 **Armour Institute** .. Feb. 26, '04	C. E. Freeman.	C. E. Freeman.	
25 **Washington Univ.** .. Feb. 26, '04	A. S. Langsdorf	A. S. Langsdorf.	2d & 4th Tuesdays
26 **Univ. of Michigan** .. Mar. 25, '04	H. S. Carhart.	G. W. Patterson, Jr.	
27 **Univ. of Arkansas** .. Mar. 25, '04	W. N. Gladson.	W. A. Treadway.	1st & 3d Tuesdays
28 **Worcester Polytechnic Institute** .. Mar. 25, '04	J. A. Johnson.	G. H. Gilbert.	Sept. 30, Oct. 14, Nov. 11, Dec. 9, 1904; Jan. 6, Feb. 10, Mar. 10, Apr. 21, May 12, 1905.
29 **Pittsfield** ..... Mar. 25, '04	F. A. C. Perrine.	D. B. Rushmore.	

JOINT MEETING

OF THE

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

AND THE

INSTITUTION OF ELECTRICAL ENGINEERS

OF GREAT BRITAIN,

HELD AT FESTIVAL HALL, WORLD'S FAIR GROUNDS, ST. LOUIS, MO., WEDNESDAY, SEPTEMBER 14, 1904.

President Bion J. Arnold, of the AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS, called the meeting to order at 10.30 o'clock a.m. and said:

This is the second joint meeting of the Institution of Electrical Engineers of Great Britain and the AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS. It was our pleasure to meet with the Institution of Great Britain in England, in 1900, and on the grounds of the Paris Exposition, in Paris, having an adjourned meeting there, wherein took place a joint discussion. At that time our British friends were our hosts and at this time it is our pleasure to have them with us in this country. This meeting is a joint meeting, and, therefore, neither institution takes precedence—it is entirely a joint affair, held in connection with Section F, of the International Electrical Congress, and will be presided over by the Executives of both societies. The members of the Congress are cordially invited to take such part in the discussion as they desire. It is hoped that this will not be the last meeting between the Institutions represented, but that we may have many of them in the future at as frequent intervals as practicable.

In accordance with the regulations of the society which I have the honor to represent it is now my pleasure to deliver the annual address of the President. President Gray will kindly occupy the chair.

(For President Arnold's Address see October, 1904, TRANSACTIONS, page 735.)

PRESIDENT GRAY: I do not know whether I am perfectly in order under the American procedure, or not, but our habit on the other side, when we receive an address from our President, is to tender him our thanks.

As President Arnold has said, during the Paris Exposition we had a joint meeting of the two Institutions, and I am very glad indeed to say that we have in this hall to-day the two gentlemen who presided on that occasion, namely, Mr. Carl Hering and Professor Perry.

I do not think that any one could even have wished to criticise, in any way, the address which has been so ably given by your president, because if any man, either on this side or on the other side of the Atlantic, is preeminent in connection with the subject he has treated, I think it is President Arnold. His name is exceedingly well known to us on the other side, and I think I am not giving away any secret in telling you that the evidence of his work which he has been tendering to us has received a very warm reception there, and the evidence is considered to be the best that can be obtained in relation to the matters with which it deals. I therefore wish, in the name of the Institution of Electrical Engineers of Great Britain, to tender to my colleague, President Arnold, our very sincere thanks for his exceedingly able address; and with your permission, I will ask the senior Past-president of the Institution of Electrical Engineers of Great Britain to second the motion—Colonel Crompton.

COLONEL CROMPTON: It is with the most heartfelt pleasure that I rise to second the motion of President Gray, that the thanks of the AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS as well as our own Institution of England be given to President Arnold for his address, which I personally feel is worthy of this great occasion—the meeting of the two Institutions.

PRESIDENT GRAY: I presume it is unnecessary to put this motion to the meeting, and I shall put it by acclamation if it meets your approval.

PRESIDENT ARNOLD: I assure you that your expression of approval is very much appreciated indeed.

We have for our discussion this morning a subject similar to that which I have treated in my address; in fact the address was written as a sort of introduction to the discussion.

We shall now open the discussion on Different Methods and Systems of Using the Alternating Current in Electric Railway Motors. This subject has received the attention of engineers interested in electric railways for the last three or four years. During the last two years it has received very energetic attention on the part of leading engineers of Europe and this country, and it bids fair to be one of far greater importance as we get more thoroughly into heavy railway work. Since I have talked to you quite a while, notwithstanding the fact that my name appears first on the program to discuss the subject I am going to ask one of the most distinguished engineers in this country, and one of the most distinguished living authorities in electrical matters to open the discussion. I have the pleasure of introducing Dr. C. P. Steinmetz, Past-president of the AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

(For C. P. Steinmetz's discussion, see page 818, November, 1904. TRANSACTIONS.)

PRESIDENT ARNOLD: It has been said that the fame of a scientific man is a quiet fame, but that is the most satisfactory

after all. It does not attract the multitude. A man is able to walk in a crowd without being pointed out, which by the way, is a very satisfactory thing to do; but he finds that when he reaches different parts of the world his name has preceded him in the circles in which he moves, so that he after all enjoys in the most satisfactory way the results of his efforts in the particular line of work which he has been following. We have many such men present to-day, and among them is one who has done excellent work in the special line we are discussing this morning. I shall now call upon one of our distinguished engineers and colleagues, Mr. B. G. Lamme, of the Westinghouse Electric & Manufacturing Co., of Pittsburg, to discuss the question further.

(For B. G. Lamme's discussion see page 827, November, 1904, TRANSACTIONS.)

PRESIDENT ARNOLD: Now, without further discussing the question, I am going to call upon a gentleman whose name is known to all of you, and introducing him, I am reminded of an anecdote about a little negro boy who sat on a log chopping away with a hatchet. A man coming along the road asked him how old he was and the boy answered: "If you goes by what mother says, I'se six, but if you goes by de fun I'se had, I'se 'most a hundred." If you judge the man who is to address you by his looks, he is a young man, but if you judge him by his experience he is "most a hundred," and is the father of the commercial electric railway. I have pleasure in presenting Lieut. Frank J. Sprague.

F. J. SPRAGUE: I feel quite embarrassed by this pleasant introduction by our worthy president and the reception which you kindly give me. The subject under discussion is one which I will not enter into at any length to-day, for I see by the hungry and thirsty look on the faces of some of the gentlemen present that one o'clock is near at hand, and that they would probably rather adjourn for luncheon than to listen to any discussions whatever.

(For F. J. Sprague discussion see page 836 of the November, 1904, TRANSACTIONS.)

PRESIDENT ARNOLD: We now desire to hear from a gentleman whose early work is known in many fields, especially in the electric lighting field. His name was carried by one of the leading electrical manufacturing companies for many years and it stands to-day on much of the material that was manufactured in the early days. He is a man who has done much research work in the early days, and considerable experimental work on the repulsion motor, a gentleman whom you all know and recently honored by electing him President of the International Electrical Congress.

(For Elihu Thomson discussion see page 837 November, 1904, TRANSACTIONS.

ASSOCIATES ELECTED OCTOBER 28TH, 1904.

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Total, 44.

SECTION II.

PAPERS AND DISCUSSIONS.

This section contains INSTITUTE matters of a permanent nature; these matters will be eventually reproduced in the bound volume compiled at the end of the calendar year.

A paper presented at the 190th Meeting of the American Institute of Electrical Engineers, New York, Oct. 28, 1904.
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THE TRANSPOSITION OF ELECTRICAL CONDUCTORS.

BY FRANK F. FOWLE.

The transmission of electromagnetic energy through the ether, by means of conducting wires whose function is that of directing and concentrating the energy flow, is accompanied by mutual interferences between transmission systems which employ in common any considerable portion of the ether. The extent to which the ether is energized, in a direction transverse to the direction of energy flow, is controlled by the design of the transmission circuit and the rate of energy flow. The energy storage-capacity of a transmission circuit is very small in comparison with the transmitted energy, but the great velocity of transmission renders possible the transmission of large energies. The conformations of the electric and the magnetic fields about a line circuit depend, in alternating-current systems, on the number of phases and on the number, size, and separation of the wires. The field at a given point due to a single-phase circuit is constant in direction but variable in intensity, from instant to instant throughout a cycle; the field due to a polyphase circuit varies both in direction and intensity.

Alternating-current transmission systems resolve themselves into two great classes, one for the transmission of power and the other for the transmission of intelligence. Power systems are characterized by: high pressure; large currents; low or moderate frequencies; only one fundamental frequency; relatively great reaction of terminal apparatus compared with line reactions; magnitude of inductive disturbances in the line usually small and important only as affecting regulation; line length less than a wave length, and the flow of energy usually

in a given direction. Telephonic systems are characterized by; low pressure; small currents; high frequencies, variable over a wide range; relatively small reaction of terminal apparatus compared with line reactions; magnitude of inductive disturbances in the line usually large and rarely negligible; line lengths usually greater than the wave lengths and often equal to many wave lengths, and the flow of energy alternating in direction and source.

The general character of the fields set up about the line is the same, whatever the system, and a consideration of

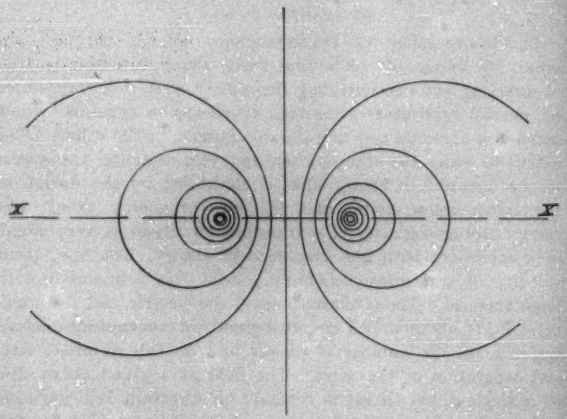


FIG. 1.

this will lead to the theory of transposition. Fig. 1 shows the magnetic field set up about a two-wire circuit; Fig. 2 shows the electric field. These two fields at all points of intersection are at right angles to each other; that is, the electric and the magnetic forces at any given point are perpendicular with respect to each other. Also, the electric pressure is constant in magnitude at all points on any magnetic flux line; or every magnetic flux line is a line of constant electric pressure. The flux density and the intensity of the electric pressure both diminish rapidly as the distance from the wires increases. An instance of this is shown in Fig. 3, which gives, in rectangular

coördinates, the flux density along the X axis of Fig. 1; Fig. 4 shows similarly the electric pressure along the X axis in Fig. 2.

For a single wire having an earth return, the solution above may be applied by considering the surface of the earth coincident with the Y axis; the wire beneath the earth's surface

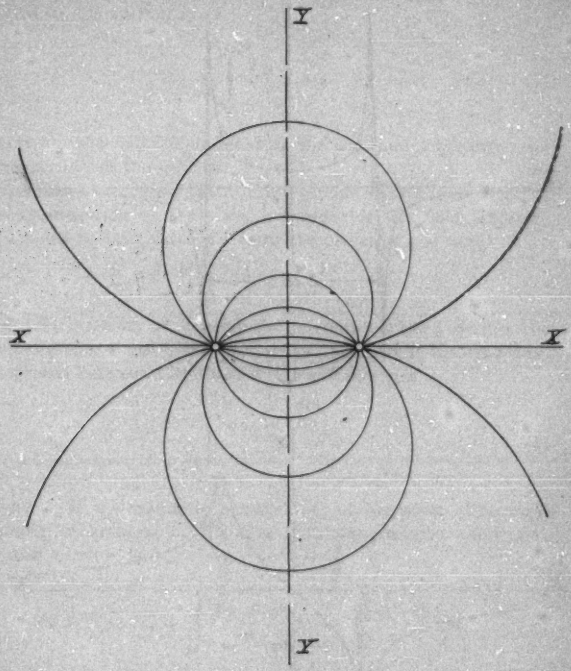


FIG. 2.

will be the electrical image of the real wire above. It will be seen that the fields due to a ground-return circuit in practice extend through a far greater volume of dielectric than in the case of a metallic circuit.

The theory upon which the above curves are based is as follows: Consider a single straight wire in free space, of radius r,

conveying a current I. The work done in carrying a unit magnetic pole circumferentially around the wire, at a radial distance a from it is

$$W = 4\pi I = 2\pi a F \qquad (1)$$

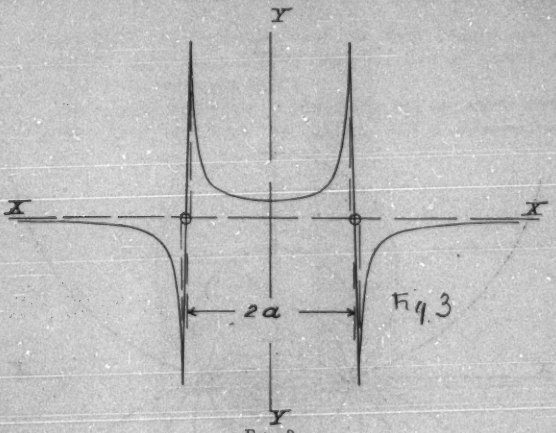


FIG. 3.

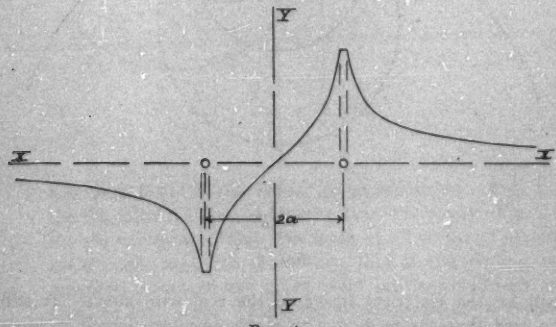


FIG. 4.

where F is the magnetic force at a. The force F acts through the point a perpendicularly to the plane containing the wire and the point a.

Therefore

$$F = \frac{2I}{a} = H \tag{2}$$

where H is the intensity of the magnetic field. In a unit length of wire the total number of flux lines encircling the wire, multiplied by the current is

$$N_1 = \int_r^\infty \frac{2\mu I^2}{x}\, dx \tag{3}$$

where x is the radial distance from the wire and μ the magnetic permeability of the medium.

Assuming a uniform distribution of the current I throughout the cross-section of the wire, we have for the field intensity at a point radially distant b from the centre of the wire,

$$\frac{\pi b^2}{\pi r^2}\left(\frac{2I}{b}\right) = \frac{2Ib}{r^2} \tag{4}$$

and this intensity is due to the current enclosed within the circumference $2\pi b$. The product of the current into the flux, integrated between the limits $b = o$ and $b = r$ is

$$N_2 = \int_o^r \frac{2\mu_1 I^2 x^3}{r^4}\, dx \tag{5}$$

where μ_1 is the magnetic permeability of the wire. The total number of linkages of the flux with the current, multiplied by the current, is

$$N = N_1 + N_2 = \int_o^r \frac{2\mu_1 I^2 x^3}{r^4}\, dx + \int_r^\infty \frac{2\mu I^2}{x}\, dx \tag{6}$$

The inductance* is therefore

$$L = \frac{1}{2}\mu_1 + \int_r^\infty \frac{2\mu}{x}\, dx \tag{7}$$

* This demonstration is due to Jackson: *Alternating Currents and Alternating Current Machinery*, p. 140.

If there is a parallel wire within the field of the first wire, distant r_{12} from it, the portion of the total flux which is linked with it, is

$$M = \int_{r_{12}}^{\infty} \frac{2\mu}{x}\, dx \tag{8}$$

and this is the mutual inductance of the two circuits.

For a two-wire metallic circuit the inductance will be double the difference between expressions (7) and (8), or

$$L = \mu_1 + 2\int_{r}^{r_{12}} \frac{2\mu}{x}\, dx$$

$$= \mu_1 + 4\mu \log \frac{r_{12}}{r} \tag{9}$$

For a single wire at height h above the earth, the inductance is

$$L = \frac{1}{2}\mu_1 + 2\mu \log \frac{2h}{r} \tag{10}$$

These expressions in henries per mile are respectively

$$L = \left(0.1609 + 1.482 \log_{10} \frac{d}{r}\right)10^{-3} \tag{11}$$

$$L = \left(0.08047 + 0.7411 \log_{10} \frac{2h}{r}\right)10^{-3} \tag{12}$$

where μ and μ_1 are unity.

The field of force without a two-wire metallic circuit is, from (2)

$$F = 2I\left(\frac{1}{r_{1x}} - \frac{1}{r_{2x}}\right) \tag{13}$$

where the point x is perpendicularly distant r_{1x} from one wire and r_{2x} from the other. From this, the field intensity along the X axis in Fig. 1 is proportional to

$$y = \frac{1}{a+x} + \frac{1}{a-x} \tag{14}$$

for points without the wires and

$$y = \frac{2x}{r^2} \qquad (15)$$

for points within the wire. Fig. 3 is plotted from (14) and (15).

Considering the case of two two-wire metallic circuits, as shown in cross-section in Fig. 5, the expression for their mutual inductance follows at once from expression (8):

$$M = \int_{r_{13}}^{r_{14}} \frac{2\mu}{x}\, dx - \int_{r_{23}}^{r_{24}} \frac{2\mu}{x}\, dx \qquad (16)$$

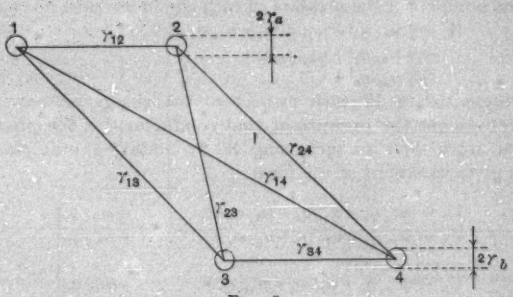


FIG. 5.

$$M = 2\mu \log \frac{r_{14}\, r_{23}}{r_{13}\, r_{24}} \qquad (17)$$

In henries per mile this is

$$M = \left(0.7411 \log_{10} \frac{r_{14}\, r_{23}}{r_{13}\, r_{24}} \right) 10^{-3} \qquad (18)$$

The foregoing expressions for self and mutual inductance may be established from the standpoint of the kinetic energy of an electromagnetic system, as shown by Maxwell* and Heaviside.†

The introduction of another circuit within the field of a given circuit does not alter the expression for the self-inductance

* Maxwell; vol. II., art. 685.

† Heaviside; Elec. Papers, vol. I., p. 100.

of either circuit. The mutual inductance between the circuits is taken care of in the general equations for the energy of the whole system.

The capacity constants are not quite so simple, because the addition of a circuit within the field of a given circuit changes the constant for the given circuit by itself; and when a third circuit is considered the constants for the two previous circuits are again altered and their mutual constant is also altered and so on, for each circuit added to the group.

Take a system of n conductors with respective charges q_1, q_2, q_3 . . . q_n, and pressures v_1, v_2, v_3 . . . v_n. The pressure of each conductor is a homogeneous linear function of the n charges and the total energy of the system is half the sum of the products of the pressure of each conductor into its charge.

$$\begin{aligned} W = &\tfrac{1}{2} u_{11} q_1^2 + u_{21} q_1 q_2 + u_{31} q_1 q_3 + \ . \ . \ . \\ &+ \tfrac{1}{2} u_{22} q_2^2 + u_{32} q_2 q_3 + \ . \ . \ . \\ &+ \tfrac{1}{2} u_{33} q_3^2 + \ . \ . \ . \end{aligned} \tag{19}$$

Differentiating W with respect to the charge on any conductor we get the pressure of that conductor, for the pressure is the work done in increasing W by adding a unit charge. This gives equations of the form.

$$\left.\begin{aligned} V_1 &= u_{11} q_1 + u_{21} q_2 + u_{31} q_3 + \ . \ . \ . \ + u_{n1} q_n \\ V_2 &= u_{12} q_1 + u_{22} q_2 + u_{32} q_3 + \ . \ . \ . \ + u_{n2} q_n \\ &\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ V_n &= u_{1n} q_1 + u_{2n} q_2 + u_{3n} q_3 + \ . \ . \ . \ + u_{nn} q_n \end{aligned}\right\} \tag{20}$$

The coefficient u_{xx} expresses the pressure of the conductor x when its charge is unity and that of all other conductors zero. The coefficient u_{xy} expresses the pressure of the conductor y when the charge on x is unity, the charges on the other conductors being zero, and $u_{xy} = u_{yx}$. Solving (20) for the charges,

$$\left.\begin{aligned} q_1 &= C_{11} V_1 + C_{21} V_2 + C_{31} V_3 + \ . \ . \ + C_{n1} V_n \\ q_2 &= C_{12} V_1 + C_{22} V_2 + C_{32} V_3 + \ . \ . \ + C_{n2} V_n \\ &\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ q_n &= C_{1n} V_1 + C_{2n} V_2 + C_{3n} V_3 + \ . \ . \ + C_{nn} V_n \end{aligned}\right\} \tag{21}$$

where C_{xx} is a coefficient of capacity and C_{xy} is a coeffiicent of induction or mutual capacity. The coefficients C are functions of the coefficients u. Maxwell* shows that the coefficients of pressure are all positive, but none of the coefficients u_{xy} are

* Maxwell; vol. I., chap. III.

greater than u_{xx}; none of the coefficients of induction (mutual capacity) are positive and the sum of all those belonging to one conductor is not numerically greater than the coefficient of capacity of that conductor, the latter being always positive; when there is only one conductor in the field, its coefficient of pressure with respect to itself is the reciprocal of its capacity; if a new conductor is brought into the field, the coefficient of pressure of any other conductor with respect to itself is diminished, the coefficients of capacity are increased and the coefficients of induction (mutual capacity) are diminished. To find the expression for the coefficients u, consider a single wire in free space, with a charge q per unit length.

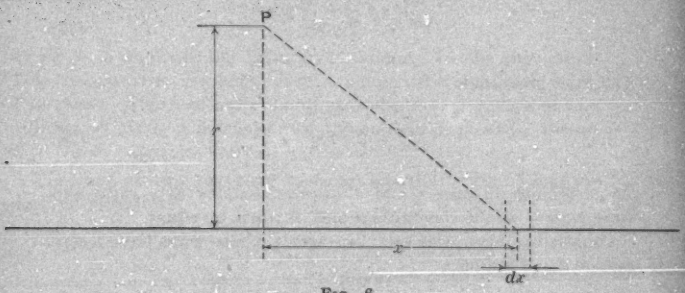


FIG. 6.

The force at P due to the charge $q\,dx$ is

$$dF_1 = \frac{q\,dx}{x^2+r^2} \tag{22}$$

and the force normal to the wire (the longitudinal component vanishes when the whole wire is considered) is

$$dF = \frac{q\,r\,dx}{(x^2+r^2)^{\frac{3}{2}}} \tag{23}$$

$$F = \int_{-\infty}^{+\infty} \frac{q\,r}{(x^2+r^2)^{\frac{3}{2}}}\,dx = \frac{2q}{r} \tag{24}$$

But the force is the negative of the partial derivative of the pressure with respect to the distance, or

$$F = -\frac{\delta}{\delta r}(V) \tag{25}$$

whence

$$V = 2q \log \frac{a}{r} \tag{26}$$

a being a constant.

In practice there is always the return conductor of opposite pressure to consider; or if the earth be the return the electrical image must be considered. The pressure at the point P, distant r' from a second parallel wire, with a charge $-q$ per unit length is

$$V' = -2q \log \frac{a'}{r'} \tag{27}$$

The total pressure is

$$V_0 = 2q \log \frac{r'}{r} \tag{28}$$

At an infinite distance r and r' approach unity as a ratio and since $\log 1 = 0$, the constants a and a' must be equal.

Considering a two-wire metallic circuit whose wires have a separation d and radius r,

$$V_1 = 2q \log \frac{d}{r} \tag{29}$$

$$V_2 = -2q \log \frac{d}{r} \tag{30}$$

$$V_1 - V_2 = 2q \log \frac{d^2}{r^2} = 4q \log \frac{d}{r} \tag{31}$$

$$C = \frac{q}{V_1 - V_2} = \frac{1}{4 \log \frac{d}{r}} \tag{32}$$

The pressure coefficient in the above case is

$$u = 2 \log \frac{r'}{r} \tag{33}$$

The pressure of the electric field along the X axis in Fig. 2 is proportional to

$$y = \log \frac{a + x}{a - x} \tag{34}$$

for points without the wires, and is constant within them. The curve in Fig. 4 is plotted from (34).

If the wires are insulated the capacity is slightly increased by the greater specific inductive capacity of the insulation. If the wires are of radius r_1 and the insulating coverings of radius r_2, (32) becomes

$$C = \frac{1}{4 \log \frac{d}{r_2} + \frac{4}{k} \log \frac{r_2}{r_1}} \tag{35}$$

where k is the specific inductive capacity of the insulation. This increase in capacity may amount to several per cent. The above equations are general and apply to a system of any number of wires; a discussion of the subject is given by Heaviside,* with examples worked out for ground-return circuits.

The case of two two-wire metallic circuits in Fig. 5 may be derived as follows:

$$\left.\begin{aligned} v_1 &= u_{11} q_1 + u_{21} q_2 + u_{31} q_3 + u_{41} q_4 \\ v_2 &= u_{12} q_1 + u_{22} q_2 + u_{32} q_3 + u_{42} q_4 \\ v_3 &= u_{13} q_1 + u_{23} q_2 + u_{33} q_3 + u_{43} q_4 \\ v_4 &= u_{14} q_1 + u_{24} q_2 + u_{34} q_3 + u_{44} q_4 \end{aligned}\right\} \tag{36}$$

The circuit conditions are:

$$\left.\begin{aligned} V_1 - V_2 &= V_a \\ V_3 - V_4 &= V_b \\ q_1 + q_2 &= 0 \\ q_3 + q_4 &= 0 \end{aligned}\right\} \tag{36a}$$

A coefficient of the form u_{xy} equals the coefficient u_{yx}. Then we have

$$\left.\begin{aligned} V_a &= (u_{11} - 2\,u_{12} + u_{22})\, q_1 + (u_{13} - u_{14} - u_{23} + u_{24})\, q_3 \\ V_b &= (u_{13} - u_{23} - u_{14} + u_{24})\, q_1 + (u_{33} - 2\,u_{34} + u_{44})\, q_3 \end{aligned}\right\} \tag{37}$$

* Heaviside; Elec. Papers, vol. I., p. 42, p. 140; vol. II., p. 303, p. 329.

But

$$\left.\begin{aligned}(u_{11}-2u_{12}+u_{22}) &= 4\log\frac{r_{12}}{r_a}\\ (u_{33}-2u_{34}+u_{44}) &= 4\log\frac{r_{34}}{r_b}\\ (u_{13}-u_{14}-u_{23}+u_{24}) &= 2\log\frac{r_{14}\,r_{23}}{r_{13}\,r_{24}}\end{aligned}\right\} \tag{38}$$

$$\left.\begin{aligned}q_1 &= C_a V_a + C_{ba} V_b\\ q_2 &= C_{ab} V_a + C_b V_b\end{aligned}\right\} \tag{39}$$

From which it follows that

$$C_a = \frac{4\log\frac{r_{34}}{r_b}}{\left[16\log\frac{r_{12}}{r_a}\cdot\log\frac{r_{34}}{r_b}-\left(2\log\frac{r_{14}\,r_{23}}{r_{13}\,r_{24}}\right)^2\right]} \tag{40}$$

$$C_b = \frac{4\log\frac{r_{12}}{r_a}}{\left[\quad\right]} \tag{41}$$

$$-C_{ab} = \frac{2\log\frac{r_{14}\,r_{23}}{r_{13}\,r_{24}}}{\left[16\log\frac{r_{12}}{r_a}\cdot\log\frac{r_{34}}{r_b}-\left(2\log\frac{r_{14}\,r_{23}}{r_{13}\,r_{24}}\right)^2\right]} \tag{42}$$

The above formulas for capacity may be expressed in farads per mile by multiplying by 0.07768×10^{-6}.

The first important conclusion from the expressions for mutual inductance (17) and mutual capacity (42) is that these two constants vanish simultaneously when

$$r_{14}\,r_{23} = r_{13}\,r_{24} \tag{43}$$

Let

$$\frac{r_{23}}{r_{13}} = \frac{r_{24}}{r_{14}} = p \tag{44}$$

Let the coördinates of one circuit be fixed, and be $(+a, o)$ and $(-a, o)$, as in Figs. 3 and 4. If the two wires of the other

circuit are on the locus of the point (x, y), for any particular value of p, (43) will be satisfied. The conversion of (44) to rectangular coördinates is

$$p^2[(x+a)^2+y^2] = [(x-a)^2+y^2] \tag{45}$$

or

$$\left[x+a\frac{p^2+1}{p^2-1}\right]^2 + y^2 = \left(a\frac{p^2+1}{p^2-1}\right)^2 - a^2 \tag{46}$$

This is a system of eccentric circles, there being one circle for each value of p. The plot of this system of circles, from (46), gives the magnetic field of Fig. 1. That is, the mutual

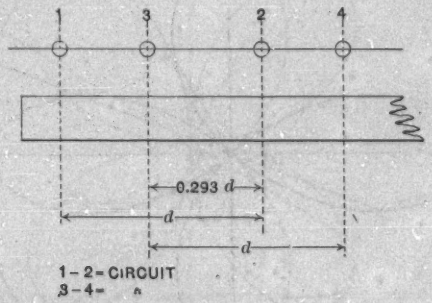


FIG. 7.

interferences vanish when the wires of one circuit are on a single flux line of the field of the other circuit, and therefore enclose none of the magnetic flux of that circuit and are at points of equal electric pressure due to that circuit.

It is seldom in practice that the conditions permit the use of the relations given in (43) and (46). A particular solution is applicable to two two-wire circuits, as independent circuits or as the respective phases of a four-wire, two-phase line. This is shown in Fig. 7.

To show how the constants of mutual inductance and capacity depend on the relative wire positions, the curves in Figs. 8 and 9 have been plotted from

$$\frac{M}{2} = \log\frac{r_{14}\,r_{23}}{r_{13}\,r_{24}} \tag{47}$$

If the circuit 3-4 always maintains a horizontal position, in Fig. 8, and the coördinates of P are (x, y), P being constrained to move in a circle, (47) becomes

$$\frac{M}{2} = \frac{1}{2}\log\frac{[(a+b)^2+c^2]^3-[2(a+b)x]^2}{[(a-b)^2+c^2]-[2(a-b)x]^2} \tag{48}$$

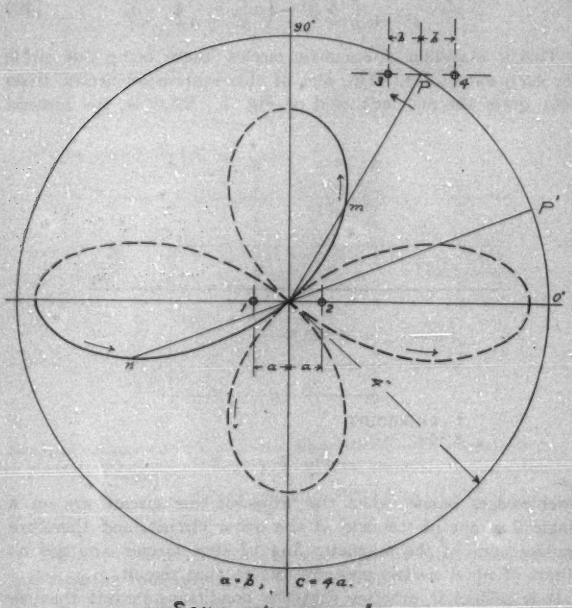


FIG. 8.

where C is given by the locus of P,

$$x^2+y^2 = C^2 \tag{49}$$

If the circuit 3-4 maintains a vertical position, in Fig. 9, and the locus of P is again the circle of equation (49),

$$\frac{M}{2} = \frac{1}{2}\log\frac{(x^2-a^2)^2+(x+a)^2(y+b)^2+(x-a)^2(y-b)^2+(y^2-b^2)^2}{(x^2-a^2)^2+(x-a)^2(y+b)^2+(x+a)^2(y-b)^2+(y^2-b^2)^2} \tag{50}$$

The curves in Figs. 8 and 9 are polar diagrams, giving the relative mutual disturbances as P describes a circle. There are four points in a revolution at which M is zero. It is possible to introduce a third circuit and so locate it that M is zero for any two, and hence for all.

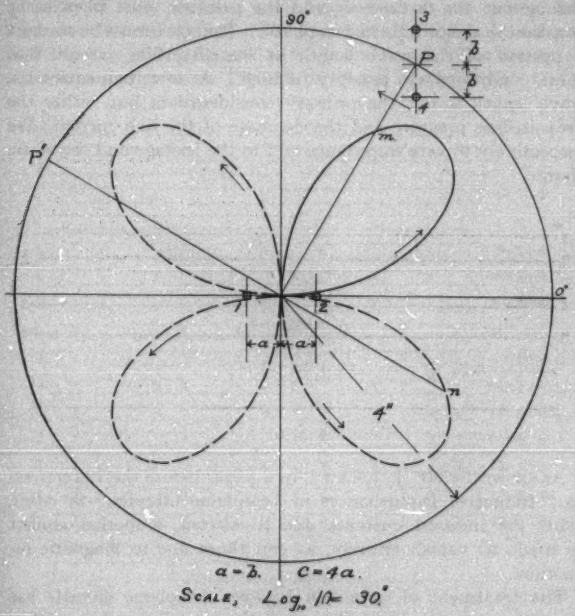


FIG. 9.

When the number exceeds three it becomes, in a practical sense, impossible to prevent mutual interferences. It is evident from expressions (17) and (42) for the mutual inductance and the mutual capacity that the interchange of wires 1 and 2 or wires 3 and 4 will change the signs of these formulas without changing their magnitude. It is evident also that interchanging both wires 1 and 2 and wires 3 and 4 will not alter the formulas in any way; that is, the transposition of one of two parallel

circuits will reverse the signs of the mutually induced currents and pressures.

Consider the circuits in Fig. 10.

The additional conditions which are necessary for the disturbances to vanish are as follows. The current in the disturbing circuit must be constant in magnitude and in phase throughout the distance l, and the pressure must likewise be constant in magnitude and in phase. That is, 1 must be so short a portion of the wave length in the disturbing circuit that these conditions are sensibly fulfilled. At low frequencies the wave length is not the primary consideration, but rather the drop in line pressure and the decrease of the line current, due respectively to wire impedance and to the leakage and the static charge.

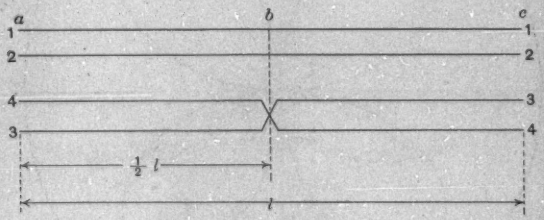


FIG. 10.

As shown by Mr. J. J. Carty, in a paper before the INSTITUTE, on "Inductive Disturbances in Telephone Circuits," in April, 1891, the induced currents due to electric induction cannct be made to vanish entirely, as can those due to magnetic induction.

The treatment of induction between telephone circuits has been by empirical rule rather than theory. It has been determined by experiment, with receivers of a given sensitiveness and transmitters of a given power, how frequently two adjacent circuits should be transposed in order to eliminate the cross-talk. Using two-mile sections, transposed at the centre, the cross-talk is distinguishable with transmission sufficiently powerful for 1000-mile service. Half- or quarter-mile sections, transposed at the centre, are satisfactory; this results in a minimum transposition spacing of one-quarter mile. The existence of cable at each end of the line, in any considerable length, will

reduce the cross-talk. It is necessary to devise different types of transposed circuits, no two transposed alike, in order to treat the cases occurring in practice. The manner of doing this is shown in Fig. 11.

The " exposure," as it is termed, of circuit 1 to circuit 2 is $\frac{1}{4}$; of 1 to 3 is $\frac{1}{4}$; of 2 to 3 is $\frac{1}{4}$; because a transposition at the junction of two sections, each transposed at its centre, has almost no beneficial effect. The exposure of 1 to 5 is $\frac{1}{8}$; of 2 to 6 and 3 to 7, $\frac{1}{8}$; of 2 to 8 and 2 to 9, $\frac{1}{16}$; and so on. The tabulated exposures are given in Fig 12, in terms of the length l of a

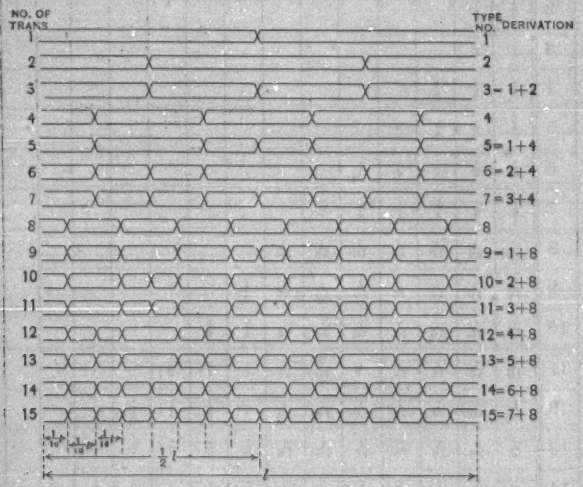


FIG. 11.

transposition section. The derivation of the types is simple; the first three are obvious. The fourth is obtained by doubling the number of divisions of the transposition section from two to four. The fifth is obtained by superposing the first type on the fourth type, the sixth by superposing the second on the fourth, etc. The composition of the complicated types is shown in Fig. 11. So far as the writer is aware this synthetical system of deriving types of dissimilarly transposed circuits is due to Mr. John A. Barrett. The method may be extended as far as desired, but 15 types are usually sufficient.

The choice of a convenient length for l is an important matter. An eight-mile section has been extensively used, but is probably too cumbersome. A much more convenient section would be one four miles in length.

If there are only a few circuits, a two-mile section may be

	Exposure of Type No.													
To	1	2	3	4	5	6	7	8	9	10	11	12	13	14
2	1/4													
3	1/4	1/2												
4	1/8	1/8	1/8											
5	1/8	1/8	1/8	1/2										
6	1/8	1/8	1/8	1/4	1/4									
7	1/8	1/8	1/8	1/4	1/4	1/2								
8	1/16	1/16	1/16	1/16	1/16	1/16	1/16							
9	1/16	1/16	1/16	1/16	1/16	1/16	1/16	1/2						
10	1/16	1/16	1/16	1/16	1/16	1/16	1/16	1/4	1/4					
11	1/16	1/16	1/16	1/16	1/16	1/16	1/16	1/4	1/4	1/2				
12	1/16	1/16	1/16	1/16	1/16	1/16	1/16	1/8	1/8	1/8	1/8			
13	1/16	1/16	1/16	1/16	1/16	1/16	1/16	1/8	1/8	1/8	1/8	1/2		
14	1/16	1/16	1/16	1/16	1/16	1/16	1/16	1/8	1/8	1/8	1/8	1/4	1/4	
15	1/16	1/16	1/16	1/16	1/16	1/16	1/16	1/8	1/8	1/8	1/8	1/4	1/4	1/2

Fig. 12.

used. A case of this sort is a ten-wire line, on a single-cross-arm, as shown in Fig. 13.

The following table gives the theoretically permissible exposure between any two circuits. The basis on which this table is computed is as follows; calculate $\frac{M}{2}$ from (47) for

each combination of two circuits; if the standard of exposure between two adjacent circuits is, say, one-fourth of a mile, then the exposure between any other two circuits will be inversely proportional to the calculated $\frac{M}{2}$ for the two latter circuits.

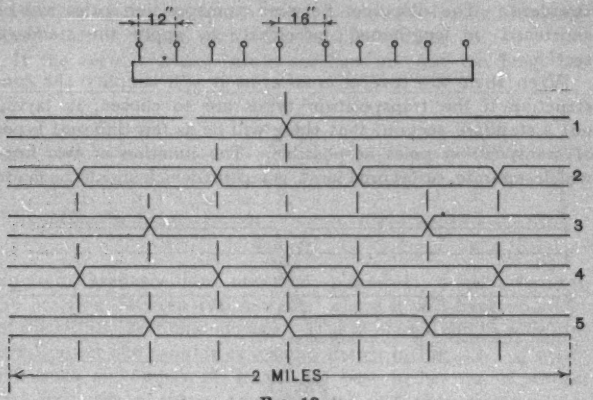


FIG. 13.

	Circuit No.				
To	1	2	3	4	5
1					
2	0.25				
3	0.90	0.21			
4	2.85	1.31	0.21		
5	4.95	2.85	0.90	0.25	

The tabular values are in miles.*

* See *Electrical World and Engineer* for Nov. 21, 1903, an article by the author on this subject, from which the table is taken.

The procedure in applying the sections to a long line is as follows: beginning at the first pole, of the open-wire line, apply the sections consecutively until the last section is approached. It is seldom the line length is a multiple of the section length, so the remainder should be a special section by itself, if over half the length of a standard section, or should be added to the last section, making a special section longer than the standard. The distances between transposition poles will be shortened or lengthened sufficiently to apply the standard section.

When there are several cross-arms it will simplify the construction if the transposition types are so chosen, in laying out a standard section, that there will be as few different types of transposition poles as possible. The junction of two lines which separate, or become joint, is a point which should be made

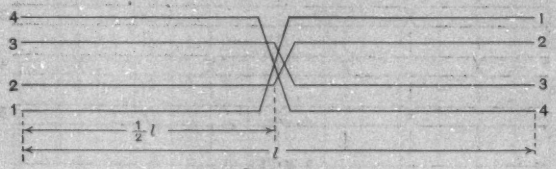


FIG. 14.

the junction of the transposition sections, as well. The 15 types shown in Fig. 11 will be sufficient for a 40-wire line, because there will be certain diagonal exposures requiring transposition only at long intervals, and these extra transpositions may be located at the junction poles between sections.

Single-wire grounded lines cannot be transposed, and for this reason are not extensively used. They may be operated for short lengths of a mile or so, without interference from cross-talk, if very low-power receivers are used. For greater lengths, there will be serious cross-talk; the low-power receiver is still necessary to remove extraneous inductive disturbances.

Phantom circuits, built up from metallic circuits, are not in extensive use. The ordinary transposition is of no effect, and unless specially transposed such circuits will cross-talk and will be subject to extraneous induction. The transposition of a phantom may be done in several ways. Fig. 14 shows a transposition in which the phantom is transposed, and its two com-

ponent circuits, while not transposed with respect to each other, are transposed with respect to any other parallel circuits but are also moved in position, thereby partly offsetting the latter transposition.

A second method is shown in Fig. 15, where the two component circuits are not transposed with respect to each other, or to any additional parallel circuits.

Another method, in which the component circuits are transposed with respect to each other, is shown in Fig. 16.

If the regular transposition sections are not too long, the

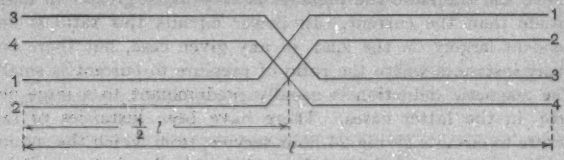


FIG. 15.

phantom transposition may be placed at a pole forming the junction between two sections, where it will have no effect on the regular sectional system. If it is placed within a section it will upset the tabular exposures shown in Fig. 12. If many phantoms are employed, it will be best to lay out a section with only the phantom transpositions and then to superpose

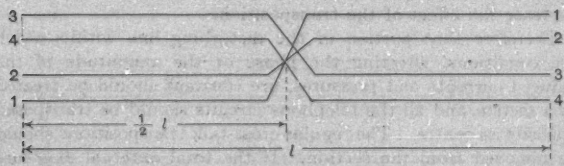


FIG. 16.

on it the additional simple transpositions to eliminate the cross-talk between the metallic circuits themselves.

When telephone lines are paralleled by power lines the transposition problem becomes more complicated. It is necessary to recognize the manner in which the disturbing circuits alter the magnitude of their influence, by reason of abrupt changes in line pressure or line current, and changes in the wire spacings. If circuit 1-2, in Fig. 10, is the power circuit and 3-4 is the telephone circuit, there will be no mutual interferences if the

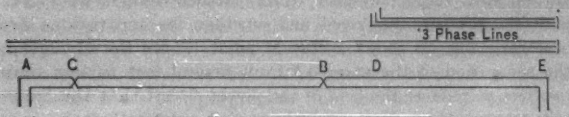
distance l is not great. That is, the percentage pressure drop in 1-2 must be small enough so that the total induced charges on the portion $a\,b$ are sensibly equal and opposite to those on $b\,c$; likewise, the percentage current loss in 1-2 must be so small that the magnetically induced pressure in the portion $a\,b$ is equal and opposite to that in $b\,c$. The question as to whether electric or magnetic induction is the greatest is complicated by the radical differences between the systems. In long telephone lines the electric induction may predominate; the impedance of an indefinitely long line is usually several hundred or a thousand ohms, and therefore the pressure is very much greater in magnitude than the current. In power circuits this ratio is dependent largely on the load, in any given case, but there are many instances where the ratio of pressure to current is small. The magnetic induction is usually predominant to a large degree, in the latter cases. There have been instances of exposure to circuits giving 24-hour service, from which the induction was heavy only during the period of load.

If the circuit 1-2, in Fig. 10, has connected to it a transformer or a branch circuit within $a\,c$, the effect of the transposition is no longer to neutralize the induction. If the transformer is at b the transposition will have the least effect. If 1-2 is a constant-current circuit and an arc lamp is cut in, the effect will be the same, as regards the efficiency of the transposition. A change in the spacing of the wires 1-2 will also decrease the effect of the transposition.

Therefore that portion of the disturbing line within which the conditions, affecting the phase or the magnitude of the induced currents and pressures, are constant should be treated as a section and all the telephone circuits should be transposed opposite its centre. The regular cross-talk transpositions should be removed from the section. If the total external exposure to the power line involves several consecutive sections, the cross-talk transpositions should be opposite the junction of two sections, at the point where the disturbing current and pressure change in magnitude or phase.

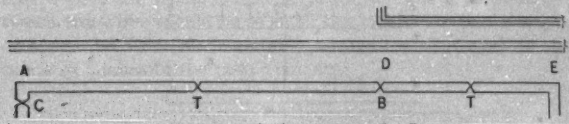
An illustration of this is shown in Fig. 17 and 18, which shows the case in which the writer first tried this method, in 1902, on a telephone line paralleling two three-phase circuits. Fig. 17 shows the initial situation, which caused service complaints. Fig. 18 shows the remedy, which eliminated the interferences entirely.

A more general case is shown in Fig. 19; this is hypothetical but illustrates various conditions. This method works well until the character of the exposure becomes complicated, and then the transpositions become so frequent as to be impracticable and, further, they frequently cannot be properly situated because of physical limitations. If the electric light and power system is developing rapidly the exposures are changed frequently by new construction. Again the telephone line may be separated from the power line by the width of a street; here the induction, while not excessive, is yet troublesome; and the theoretical transposition system to meet the conditions of ex-



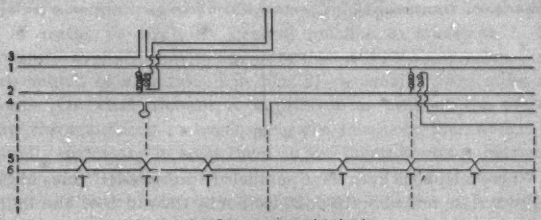
B and C are cross-talk transpositions, ½ mile apart.
Only one telephone circuit is shown for simplicity.

FIG. 17.



All telephone circuits are transposed at T.

FIG. 18.



1–2 = Constant potential circuit.
3–4 = Constant current circuit.
5–6 = Telephone circuit.
T = Induction transpositions.
T′ = Cross-talk transpositions.

FIG. 19.

posure is just as elaborate as though one line were beneath the other. Twisted pairs or cable will meet this condition, although either remedy impairs the telephonic line efficiency. A prior consideration is whether the power wires are not separated, with respect to each other, farther than is necessary with the pressure employed and whether the separations are uniform. Fig. 20 shows a case in point, where the change in the separation of the wires *a b* from several feet to less than two feet so reduces the field of the power circuit that the cross-talk transpositions in the telephone line practically take care of the induction.

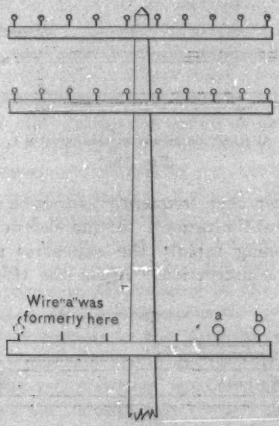


FIG. 20.

Where telephone lines have paralleled transmission lines along highways, separated by 15 or 20 feet, or by the width of the highway, the following practice has been employed. All the telephone circuits are transposed at every tenth pole—40 poles per mile—the cross-talk transpositions occurring midway, so that transposition poles are five spans apart, the cross-talk and the induction transposition poles alternating. This practice, while it is somewhat uncertain of producing the best results, is probably best suited to certain requirements,—where the method of sections would not produce any better results because of the physical unevenness and crookedness of the right-of-way.

Not infrequently high-pressure systems are transposed for their internal protection. When telephone circuits are on such pole lines, the transpositions in the power circuit may be availed of to reduce induction in the telephone circuits, but in the case of separate telephone circuits, on a parallel pole line of separate ownership, it seems wiser to treat such transpositions as neutral points—to be opposite the junction of two transposition sections of the telephone line. The question of where to locate telephone wires on high-pressure lines and how to protect them contains material for a paper by itself. In general the induction from a three-phase line is slightly greater than from a single-phase line having the same wire spacing and current per wire and a pressure equal to the Δ pressure. The separation between the wires should be as small as consistent with the length of span and their plane suitably arranged with respect to the plane or planes of the power circuits.

FIG. 21.

A three-wire, three-phase line will have two transpositions within a section, as in Fig. 21; two complete sections are shown.

It seems to be fairly general practice to transpose high-pressure systems, but it has been the writer's observation that the length of a section, l in Fig. 21, is usually three miles at least. On that account it is difficult to avail of the power line transpositions in transposing the telephone line, and it is usually necessary to treat them as the junction points between adjacent sections.

On account of the very low frequency and the high ratio of pressure to current customary in high-pressure practice, there are usually no inductive interferences if the power and the telephone lines are separated by the width of a highway or 30 to 40 feet, because the regular cross-talk transpositions are sufficient.

In the case of a single telephone circuit paralleling a power circuit, the frequency of transpositions is a problem requiring calculation in any given case, because of the lack of standard

practice in regard to wire spacing and circuit location. The writer made a series of listening tests with a bipolar receiver of 70 ohms resistance to determine the permissible current at low frequencies which would not interfere with telephonic transmission over the longest lines—1000 miles and upwards. The circuit is shown in Fig. 22.

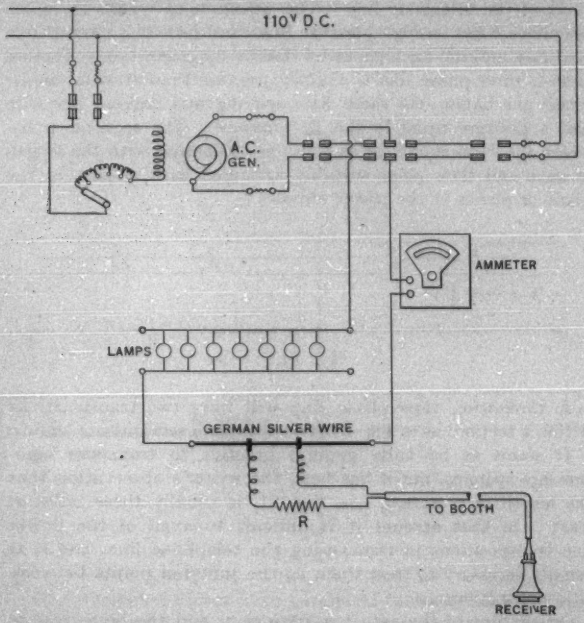


FIG. 22.

The method was that of deriving a very small known pressure —not a sine wave—from a non-inductive resistance and inserting a very large non-inductive resistance R (1000 to 20 000 ohms) in series with the shunt circuit containing the receiver. The listening tests were made by four observers, who adjusted R to the minimum permissible value, in their estimation. The average results are plotted in Fig. 23.

Naturally these results, based on ear measurements, are not highly precise, but they represent very small disturbances and are safe practice. In the case of short telephone circuits on power lines, used for private purposes, the receiver power may be much reduced and the permissible terminal current greatly increased. The method is shown in Fig. 24; the condenser is not wholly essential, but it increases the selective action.

The general theory of mutual disturbances in parallel cir-

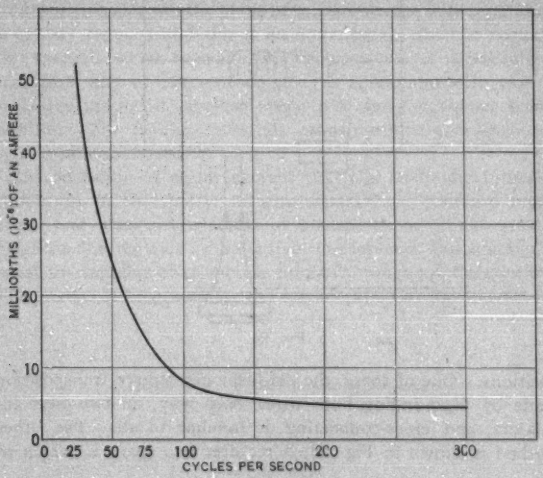


FIG. 23.

cuits, in complete form, is too elaborate to introduce here. It may be found in Vol. I. of Heaviside's Electrical Papers.*

The question of leakage is a consideration prior to that of transposition, for the theory of transposition rests on the hypothesis of electrically balanced circuits. The ordinary pony glass insulator seems to be sufficient where there are no high pressures on the same pole line. In cases of joint lines and of telephone circuits on high-pressure lines additional insulation, in the way of heavier insulators, often seems to be necessary. An elabo-

*Electrical Papers, vol. I, on "Induction Between Parallel Wires."

rate discussion of what constitutes good insulation is not in place here, but the best construction in this respect is the first essential to successful transposition.

There are two types of construction in use, in making trans-

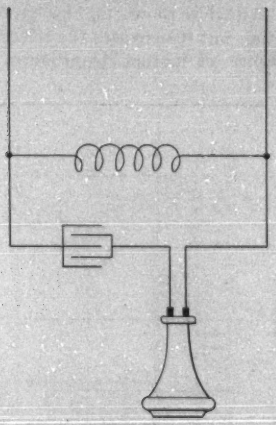


FIG. 24.

positions. One of these, the old-fashioned square transposition made by dead-ending both wires, each way, on two-piece insulators, and cross-connecting, is familiar to all. The other method is shown in Fig. 25; it requires two spans in which to

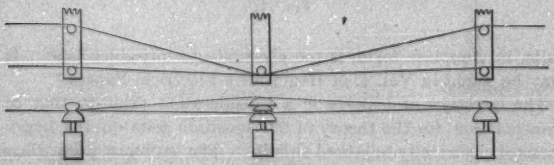


FIG. 25.

complete the entire transposition. It is known as the "Murphy" and the "single-pin" transposition, and is coming into general use.

It has the comparative advantages of less first cost and

simpler construction. It can be cut in at any time, cut out, or moved several poles, at less cost and with much less work than in the case of a square transposition. If transpositions occur frequently, every $\frac{1}{2}$ or $\frac{1}{4}$ mile, the line capacity is increased a few per cent. and the line inductance diminished, with a consequent slight increase in attenuation. The square transposition has the advantage of concentrating the entire transposition within a very short length and of not altering the plane or the separation of the wires. While the single-pin transposition changes the plane of the circuit, the wire separation is greatly reduced and this is an advantage. Since it requires two spans in which to make this transposition, it is possible to transpose only at every other pole, as a maximum, in case of excessive induction, against every pole for the square transposition. For regular cross-talk transpositions the single-pin type is now preferred.

In conclusion, it seems evident that the recommendation of standards, in the matter of wire separations, standard cross-arms, and standard systems of transposition, would greatly facilitate the removal of inductive interferences and materially assist the builders of telephone circuits throughout the country. This matter is suggested for the consideration of the INSTITUTE.

Discussion at St. Louis, Sept. 14, 1904, on "Different Methods and Systems of Using Alternating Current in Electric Railway Motors."

Mr. Steinmetz: The problem which we have before us here for discussion—the problem of the direct application of alternating currents to electric railways—is not a new one, but it has become of primary importance and interest in the last few years. The early pioneers in electric railroading, 10 or 15 years ago, started the development of the alternating-current railway motor, and prominently among them may be mentioned Mr. R. Eickemeyer and Mr. Vandepoele, who designed alternating motors for railway purposes and investigated their characteristics. However, very little progress was made in this field for many years, for a number of reasons; one being that in those early days frequencies of 125 to 130 cycles were customary, far higher than we are using now and the difficulties of the problem were thereby increased so formidably that advance was necessarily very slow. In addition the very rapid development of the direct-current railway motor fully occupied the attention of all electrical engineers, and therefore the less urgent field of the alternating-current motor was necessarily somewhat sidetracked. Then the alternating-current polyphase induction motor came into the foreground, showed its superiority over other types of motors for stationary work, and impressed the engineers to such an extent that for a long time it overshadowed the work done by the early investigators on the variable-speed alternating-current motor, that is on motors with series characteristic. Attempts then were made to introduce this very successful polyphase induction motor into electric railway work, attempts which have not been successful to any great extent. In the meantime, in the United States the synchronous converter was developed and became a standard piece of apparatus familiar to everybody—standard as much as the direct-current generator and the alternating-current generator; and experience with such synchronous converters shows that for electric railway work, for the violently fluctuating loads on the railway system, the synchronous converter is superior even to the direct-current generator: the absence of armature reaction, the phase control of pressure feasible in the converter, and corresponding close pressure regulation makes it specially able to withstand and take care of very violent fluctuations of load and to carry overloads which no direct-current generator can carry. This apparatus became standard, and with its introduction the field of the direct-current railway motor could—the distances which could be covered by the direct-current railway—was extended practically without limit, and a field opened which has been exploited in the last years, which was the field dreamed of by the early pioneers; the difficulties, however, being overcome, not by the development of the alternating-current motor, but by the development of

methods of transmitting alternating currents and transforming them into direct currents along the routes, in synchronous converter sub-stations.

Now, however, in the last year or two, with the still further development of the electric railroad, we have approached and in many instances reached the limits of applicability of this synchronous converter. The synchronous converter is a piece of machinery which requires sub-stations, requires some attendance, and as a necessary result has a high economical efficiency only where the traffic is sufficiently condensed to warrant the maintenance of sub-stations within relatively short distances from each other. Where the number of trains is less or the power per train greater than can be supplied at 500 volts from sub-stations, without excessive expenditure in line conductors, and too excessive fluctuations of load, pressures are required higher than can be utilized efficiently in direct-current motors, and there we strike the limit of the synchronous converter, and the alternating-current motor has to come in.

Personally the speaker does not believe that the alternating-current motor will make very serious inroads in the field now occupied by the direct-current railway motor. Nor does he believe that direct-current railway systems will be changed into alternating-current railway systems; but what he expects of the alternating-current railway motor is that it will find a field of its own, a new field; just as when the alternating-current method of distribution was developed in this country, it did not displace the direct-current method of distribution which occupied the centers of our large cities, but it found a field of its own, a field which has gradually developed so as to be equal in importance if not superior to the field occupied by the direct current. Hence, to conclude these remarks, what the speaker expects of the alternating-current railway motor is that it will find and develop a field of its own, that field which the direct-current railway motor cannot reach—suburban and interurban service, long-distance service, secondary railway service.

When considering the technical aspect of the subject before us for discussion to-day, the relative advantages and disadvantages of the direct- and alternating-current railway motors, we have to consider, first, the character of the problem we have to meet in electric propulsion; secondly, the character of the apparatus which we have available to solve these problems; thirdly, the additional features imposed upon the problem, or conditions more or less outside of the problem, as, for instance, the condition of the electrical industry at present, the existing investment in direct current and in steam railroads, which have to be taken into consideration when discussing any new system of railway propulsion.

Regarding the characteristics of the different types of motors —the direct-current series motor now in universal use for railroad work, the polyphase induction motor proposed, and, to a

certain extent tried in the last years for railway work, a motor eminently successful in stationary work—and the alternating-current single-phase railway motor with commutator, the speaker has, in a paper before the International Electrical Congress, given the results of a theoretical investigation and discussion of these different motors and shown the speed-torque curves, or characteristic curves of these motors in relation to each other. In Fig. 1 is given a comparison of the typical speed-torque curves of the different types of motors.

In general, the characteristic of the polyphase induction motor is essentially that of a constant-speed motor, with shunt-motor characteristics; that is, it can efficiently operate over a certain limited range of speed only, cannot exceed the synchronous speed, and when operating below its normal speed, it operates less efficiently; that is, when operating at a lower speed than normal, or approximately synchronous, as can be done by a rheostat in the secondary circuit, the polyphase induction motor merely wastes that part of the power corresponding to the difference between its actual speed and synchronous speed. Or in other words, at low speed the induction motor consumes the same power which it consumes with the same torque at full speed, though its power output is reduced in proportion to the speed, and its efficiency correspondingly.

In the direct-current series motor the torque developed by the motor decreases with increase of speed, and inversely with increasing load the speed of the motor decreases. The maximum torque of such a motor occurs in starting. All variable-speed commutator motors, alternating and direct, more or less differ from each other in the rate at which the torque varies with the speed, and that brings us to a consideration of the requirements of electric propulsion.

Important classes of work to which an electric motor may be put in locomotion are: first, city railway or tram car work; secondly, rapid transit service as an elevated and underground roads; thirdly, suburban and interurban service; fourthly, trunk line passenger service; fifthly, long distance freight service, and sixthly, elevator service.

Now, discussing these briefly in succession. The city tram car service is characterized by its frequent stops of irregular duration, at irregular intervals. To maintain good average speed it is therefore essential that the motor should get under way after the stop as rapidly as possible; that is, have a very high starting torque and accelerating torque, and carry this high torque up to a considerable speed. Beyond this speed, then, the torque of the motor should decrease fairly rapidly down to the torque required to run on a level track, which we may assume roughly to be at twice the speed to which the high torque of acceleration should be maintained. In addition thereto, it is necessary that the motor should accelerate efficiently and that it should be able to operate efficiently at low

speeds in those city districts where the general traffic is dense and where it is not possible to run at high speeds. The characteristics of this type of motor are preeminently given by the direct-current series motor. If we assume the torque

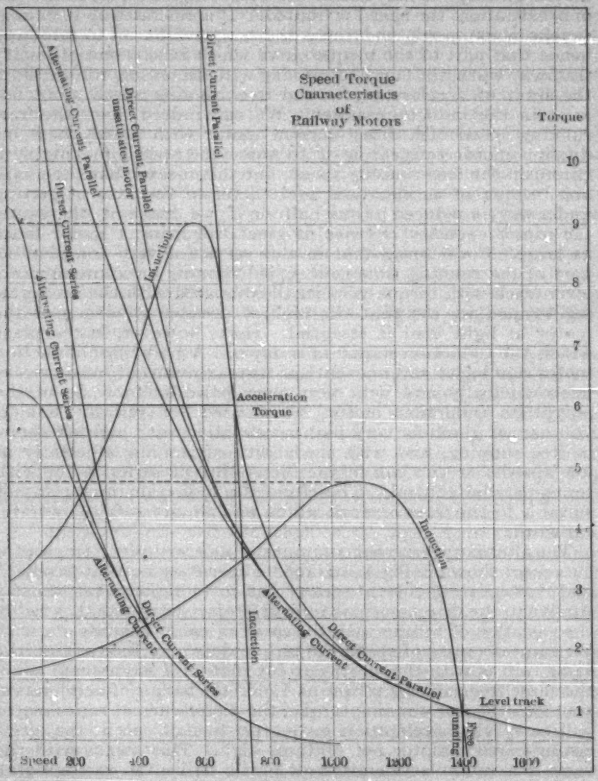


FIG. 1.

required to run on a level track as 1, probably the starting or accelerating torque may be something like six times as high. At that torque we start and run up to considerable speed, and then strike what is called the *motor curve*, and after cutting

out all regulating devices, accelerate with decreasing velocity up to the free-running speed. Such a curve, that of a typical direct-current railway motor, is given in Fig. 1, marked "direct-current parallel" and "direct-current series." The induction motor, although it may accelerate with a high torque, at the end of acceleration, the speed is limited. It accelerates up to or near synchronous speed, and there the torque falls off to zero; and hence that part of the torque curve which is so essential to city tramway work, the curve of running with decreasing torque, from the limit of acceleration to the free running speed, does not exist in the induction motor. We can indeed reach the free-running speed of a direct-current motor with a polyphase induction motor by gearing it to twice the speed, making synchronism the free running speed, but this means that the available torque of acceleration, and therefore the rate of getting under way, is reduced by one-half or if we make it the same, the motor capacity is twice as great, requiring a motor twice as large. Considering that in this service a very considerable part of the running time is occupied running on approximately level track with torque very small compared with the accelerating torque, we see that the highest possible efficiency of the motor at light load is essential. Here, however, is the place where the induction motor falls down. A polyphase induction motor running at, say, one tenth of its maximum output runs very uneconomically and with very poor power-factor. So in the polyphase induction motor, when used for railway service, you cannot combine very high acceleration with high efficiency in free running, and with the ability of running efficiently at low speeds, as you can in the direct-current series motor with series-parallel control. Therefore, the induction motor is not suitable to the class of work which we call city service or tram-car work.

The alternating-current commutator motor of which two sets of curves are shown in Fig. 1, marked "alternating-current parallel" and "alternating-current series" has characteristics very closely similar to the direct-current railway motor, except that possibly the variation of torque with the speed is less. That means, with the same decrease of speed the torque does not increase at the same rate as with the direct-current motor; if we assume again the same free running torque as 1, and the torque of acceleration six times the free-running torque, the direct-current series motor will carry the acceleration torque up to half speed; the alternating-current motor not quite as high. This means with the same maximum acceleration you will strike the motor curve at a lower speed, accelerating on the motor curve, you get under way, then, slightly slower, or to get the same average acceleration you have to start with a higher maximum acceleration. Now, this is an advantage in some cases in so far as you run for a longer period of time and over a wider range of speed on the motor curve, that is without controlling devices, hence

in the most efficient manner possible, and thereby make up to a considerable extent for that power which the alternating-current motor inherently loses by its slightly lower efficiency due to the alternating character of the magnetic field, and the losses by magnetic hysteresis in the motor field of the alternating-current motor which do not exist in the direct-current motor. This difference in the speed-torque curve of the alternating-current series motor, compared with the direct-current series motor, is due to the lower magnetic density used in the alternating-motor field, and, at low speeds, also to the e.m.f. of self-induction. The first phenomenon, therefore, also occurs in an unsaturated direct-current series motor (Fig. 1), and such a direct current series motor therefore has at high and medium speeds the same characteristic as the alternating-current motor. It is undoubtedly true that alternating-current motors can be designed to give very closely the same characteristics as the standard direct-current series motor. However, the motor as it is before us at present reaches the motor curve at a lower speed, therefore with the same maximum acceleration, gives a lower average acceleration up to full speed, or with the same average acceleration requires slightly higher maximum acceleration.

Coming now to the second class of service, rapid transit service, here the problem and the conditions of operation are almost identically the same as in city service, except that the units are larger, the speeds are higher, the stops not as frequent, absolutely, but about just as frequent relatively in compairson to the maximum speed of the motor, so that we can directly apply our considerations to rapid transit service—regarding a comparison of polyphase induction motors of alternating current commutator motors, and of direct-current motors.

In interubran and suburban work, that is, in railroads running out from the cities far across the country into the suburbs or into other cities, we have a much lesser frequency of stops. That means that rapidity of acceleration is of lesser importance, and we can well get along with a lesser average torque of acceleration, but we must have the same surplus torque as on city service work, or rather a greater surplus torque, because, while in city service and in rapid transit service where the distances are relatively short, we can count on maintaining fairly constant pressure in the supply system, we cannot to the same extent count in this on interurban and suburban service where we are far away across the country, except by investing much greater sums in line conductors and feeders than is commonly economically desirable or feasible. Hence, in this service the motor should have a greater surplus torque than in city service, so as to get a sufficient margin to start the train or the car under the most severe conditions on an up-grade or an overload, even if the pressure in the system is low. The motor which is most sensitive to pressure variation is the polyphas

induction motor. The maximum torque which this motor can give necessarily cannot very much exceed the acceleration torque without badly spoiling the characteristics of the motor either electrically or mechanically; but the maximum torque varies with the square of the pressure and hence rapidly decreases if the pressure of the system is low. In the motors with series characteristics, however, like the single-phase commutator motor, the direct-current series motor, the torque does not depend on the pressure; or rather, while the maximum torque so depends, the theoretical maximum torque which you get from the motor when standing still is so far in excess of the torque of self-destruction, or rather of slipping the car wheels, that it is not reached, and the effect of variation in the supply pressure is merely a variation in the motor speed. That is, if the pressure is low in the system, the direct-current motor and the alternating-current commutator motor runs at lower speeds, but still is able to give the same torque, while the polyphase induction motor runs at the same speed, but is not able to give the same margin of torque, and at a certain load falls down or does not start. That means that in designing a system of transmission and distribution for alternating-current commutator motors or direct-current motors we are permitted to design the system for the average drop of pressure in the system while in designing it for induction motor service, we have to take into consideration the maximum drop of pressure in the system which is very much greater than the average.

For interurban and suburban service we require an excess overload in torque, but do not require an acceleration up to high speed. The alternating-current commutator motor appears to be preeminently satisfactory in this work, and there is where the speaker believes it will be used extensively, and where the advantage of a high-pressure trolley and of the absence of substations is specially important.

In trunk line passenger service the rate of acceleration as given at present by the steam locomotive is very much less than every-day practice in electric railroad service. So here we do not need this excess acceleration torque sustained up to high speeds. Here, again, we find a field where we may apply the alternating-current commutator motors. The polyphase induction motors could be used if the question of pressure supply did not come in, as discussed above, and if furthermore the limit in speed of the induction motor was not so objectional in passenger trunk service, where, more than anywhere else, we desire to get the full benefit of the track by running at the highest safe speeds wherever the track is level. This the induction motor with its limited speed cannot do.

In trunk line freight service, the same considerations come in, except there the speeds are relatively low, the train weights great; and it is more than anywhere essential to have a very large surplus torque available to get under way or to hold the

train on a grade. You must, therefore, in this class of service, just as in suburban and interurban service, have a motor running efficiently at light load, but being able to give very high torque, although it does not need to carry this torque up to high speeds. On the contrary, it is not desirable in freight service that the motor should sustain a high torque up to high speeds, because that would mean the consumption of very large power. In freight service the highest possible economy is especially necessary, and the highest possible economy means the least fluctuations of power consumption; that means on up-grades you would desire to go slow and reduce the power consumption and get the high speeds on the level track.

In mountain railways and such classes of work, the running torque is of the same magnitude as the starting torque, and so the load on the motor is more nearly constant than in any other class of railway work, and on the down-grade the motor is preferably used for braking, by returning power into the line. Here then the polyphase induction motor appears well suited, and is indeed being used successfully. Such service, however, is in its character more nearly akin to elevator service than to railway service.

In the discussion so far we have considered the requirements of the different classes of railway service, irrespective of extraneous conditions. When considering the alternating-current motor and the direct-current motor, we have to take in view what exists at the present time in this country and abroad. There exists the enormous network of steam railroad and of direct-current electric railways. The steam locomotive is a unit of very high efficiency, but a very large unit. It therefore for efficient operation requires the massing of traffic in heavy trains, and results in less frequent but large trains. This has practically rearranged and reorganized the whole system of locomotion by collecting it into a small number of very large units. That is not the most efficient manner of operating electrically-propelled vehicles, but rather the contrary. Furthermore, you have to consider that every city and almost every village has a direct-current railway system. Now, the main and most important features by which the electric railway motor and electric propulsion has gained and is gaining rapidly in competition with the steam locomotive, appears to me to be the frequency of headway and the absence of passenger stations, not the speed, which frequently in electric lines is lower than that on steam railways paralleled by them. The electric railway picks up its passengers anywhere in the city and deposits them anywhere and it does not require them to consult time tables, but runs its cars so frequently that the passenger can always find a car within a few minutes at any point; on the other hand, the steam locomotive requires you to consult a time table and go to a depot. As soon as the electric railroad gives up this advantage which has just

been mentioned, one of the main advantages of the electric railroad over the steam railroad will be lost, and this, therefore, is the feature which has to be kept in view. It means that whatever type of motor may be adopted in interurban or suburban service, etc., it must be able to carry the passengers through the cities over existing railways.

The existing railways are direct-current railways, and probably will remain so. That means that the long-distance motor, at least the suburban and interurban motor, must be able to run over the direct-current system. Hence, it must be a type of motor equally applicable and capable of operation on a high-pressure alternating-current or on the 500 volt direct-current system.

Taking this for granted the methods of control must also be as simple as possible, that is, the same control for alternating as for direct current. Even if the motor could be used on direct current and alternating current, if we would have to carry a double system of control, one for city service and direct current, the other for long-distance service and alternating current, this would be a very serious handicap. It means that really to solve the problem before us, or extending the electric railroad into interurban and suburban service, and into the field now occupied by the steam railroad systems, and into new fields not yet developed, to a large extent not even dreamed of, that we must have a motor which with the same controlling appliances and the same characteristics, can run either on the high-pressure alternating circuits or on the existing direct-current circuits.

Furthermore, the enormous investment in electric railway systems existing at present has all been made, in the large systems, on 25-cycle, three-phase apparatus. That means that we shall have to continue to operate at 25 cycles. It may be preferable, possibly, to run at lower frequencies, or it may be preferable to run at higher frequency in this instance or that instance, but regardless of whether it is preferable or not, if it can be done on 25 cycles, it will have to be done on 25 cycles, and if another frequency had to be used, it would be a very severe handicap to the new system. The speaker is glad to say that there is no doubt that 25 cycles is the frequency best suited to the alternating-current single-phase railway motor.

PRESIDENT GRAY: Dr. Steinmetz's remarks have been so clearly stated and so closely reasoned out that they do not give us much chance for discussion, but, the speaker is glad to refer to an English colleague, Professor John Perry, upon whom he calls to take part in this discussion.

PROFESSOR PERRY: The speaker has to confess that he is not prepared to take part in the discussion. We have had the address of President Arnold and this excellent address of Professor Steinmetz, and two such addresses in one morning we have never had before. Clearly, they are men who have

thoroughly studied the subject, and in view of what they have said, the speaker thinks what it comes to is this—that everything seems to depend to a very great extent as to what is to occur in connection with the electrification of steam railroads in the next ten years, on the success of the single-phase alternating-current motor. Of the progress that has been made by the General Electric Company and the Westinghouse Company, the speaker had heard a great deal before leaving the other side, and it is one of the things that he promised himself to learn something about during his visit here. He has not yet been able to do much in the way of getting accurate knowledge on the subject. He has been on a tram-car at Schenectady, the motor of which was driven by direct current and the car ran well; and then he would get on another car, and was told that the motor was driven by alternating current, and it seemed to run just as well, so that he was not able to acquire any knowledge. He had no means of experimenting or ascertaining what the efficiency of the various arrangements were. Some 10 or 12 years ago he was tremendously interested in the single-phase alternating-current motor, perhaps for a selfish interest, as he had invented a system of traction which required the use of that system. He supposes we are all tremendously interested in this thing, and are all anxious to learn what we can about the alternating-current motor. The speaker wanted to go to the section in which Mr. Steinmetz was giving an account of the work yesterday, but was told it was his duty to attend a discussion upon the subject of electromagnetic units in another section, and as a man cannot be in two places at once, he had to attend to his duty as it was pointed out to him. In these circumstances, he can only say that he should like to hear the discussion of this subject proceed further before he shall feel able to take any part in it.

B. G. LAMME: Away back in the dark ages of electric traction, about 15 years ago, there was great confusion in the types of apparatus used. There were all kinds of motors and all kinds of apparatus on the car. They only had one property in common—they were all direct current. After putting a number of these systems into commercial use it was discovered that certain types of apparatus were superior to others, and those particularly interested in the manufacture of such apparatus followed up this matter to ascertain what properties were of the greatest value. It was gradually discovered that one type of motor was taking precedence of all others, namely, the series motor. Practically all development for a certain time was in the direction of the direct-current series motor.

The reasons which led to this were partly based on theory and partly on practice. The series motor gave the effect of a cushion on a car. The motor is inherently a variable-speed machine and automatically varies its speed with the condition

of the load. That was discovered to be a matter of first importance in the smooth operation of electric cars. Also the motor automatically increases its torque in a greater proportion than the current, which is of great importance in regard to starting and acceleration. These points were possibly not as well understood at that time as at present, but experience showed that certain equipments were superior to others and development was along that line.

After a few years, when the motors had reached standard proportions and practically but one type was used, a second limitation was discovered; namely, in the transmission conditions. It was found that in the extension of the railway system, the ordinary 550- or 600-volt direct-current system was becoming cumbersome, and it was evident that some method of transmitting power at higher pressure and transforming to lower pressure for utilization would be necessary. The most evident method was naturally to transmit by alternating current and convert to direct current, in order to use existing car equipment. This led to the use of motor-generators, and later to synchronous converters.

The motor-generator was found to fit the existing alternating system fairly well, but in the development of the synchronous converter the manufacturers discovered a great difficulty in existing systems. The frequencies of 125 and 133, which were the standards for many plants, were entirely unsuited for synchronous converters and also not well adapted for synchronous motors. Another frequency, coming into general use, namely, 60 cycles, was found to be possible for use with synchronous converters, but the difficulties of design were very great in that case, and the synchronous converters were rather heavy and cumbersome.

At that time there was fortunately a new frequency adopted which was of prime importance in the development of the synchronous converter, namely, 25 cycles. So far as the speaker knows, the origin of that on a large scale, was as follows: in the Niagara Falls power plant, when it was first laid out, the engineers for the power company had arranged for a frequency of 2000 alternations per minute, or 16⅔ cycles per second. They wished to use 8-pole machines, running at 250 revolutions. The company which the speaker represents, which was one of the prominent bidders on the contract, objected seriously to the proposed frequency, as it was considered entirely uncommercial and also not suited for the best design of machine. The engineers of this company recommended 4000 alternations per minute or 33⅓ cycles per second. That was considered extremely low compared with anything then in use. As we could not come to any agreement to use that frequency, we finally compromised on 3000 alternations per minute, or 25 cycles per second, and the first Niagara machines were built in that way. There were various reasons for the adoption of a low frequency, one of which was that

commutator type of motors might possibly come into use. Another reason was that it was better adapted to synchronous converters, but it was admitted that 33⅓ cycles would also be satisfactory.

After the Niagara Falls plant was installed, there was then a precedent for the adoption of this frequency for large units, and the manufacturers began to build apparatus of this frequency for the Niagara Falls plant and also adopted it for other plants. This opened quite a field for the synchronous converter and it soon began to be extensively used for railway work, as it was recognized that this was the link needed for extending the direct-current system. Even at the early date of 1893 and 1894 it was believed by many engineers that the synchronous converter was simply a machine to meet an emergency condition, that it would not last, that the time would come when synchronous converters would be dropped from the railway service, but as the most convenient and apparently the best solution of the problem, it was adopted extensively. About that time electric railway service began to be greatly extended and synchronous converters have thus come into very general use. By the use of synchronous converters, the advantages of the alternating-current system in transmission are obtained and the advantages of the direct-current system with the series motor were retained. Distances could be extended indefinitely by increasing the number of synchronous converter stations and raising the pressure of the alternating-current lines.

Shortly after this system came into general use it was recognized that a purely alternating-current system, in which purely alternating current was supplied to the motors, would be advantageous and considerable work was done along that line. The polyphase motor apparently had the field, and naturally the manufacturing companies took up the question of the application of the polyphase motor to traction work. The company which I represent, the Westinghouse Electric and Manufacturing Company, took up this question in an active way about 1895, and built two motors of 75 h.p. each for traction work. These motors were equipped with collector rings and rheostatic control and tests were made in regard to performance, both with straight rheostatic control and with the now well known "tandem" control, in which the secondary of one motor is connected to the primary of the other to obtain half-speed conditions. Even with this latter arrangement it was found that the motors would not compare at all favorably with the direct-current motor or the system with the direct-current system using rotary converters, and this work was abandoned. It was recognized that the polyphase motor did not possess the proper series characteristics which long experience had shown to be so necessary for railway work. Other experiments along this line were made, using polyphase motors wound for two or more speeds, and two 100 h.p. motors were built which were wound

for several speeds. While this was better than the other arrangements, it still appeared that this was not a solution of the problem. Previous to this time the company had done some work in the direction of using single phase, but not as a solution of the problem which presented itself in 1895 and later.

In 1892 the question of the use of the commutator type alternating-current motor for railway work was taken up. Two motors of nominally 10 h.p. each were designed and built. These were built for a frequency of 2000 alternations per minute, or 16⅔ cycles per second. They were mounted on a car and were operated for a while, but the system was not a success. In the first place the pressure used—400 volts as compared with 550 in the direct-current motor—was rather low. It was considered that as 550 volts was the limit in the direct-current motor, 400 volts would be the limit with alternating current. The motors were tested on a track of iron rails with practically no bonding. The track drops were excessive and the pressure fluctuations were great. The generator used—of about 20 kw. capacity—was entirely too small for this work and it was not adapted to handle the inductive loads which were found with alternating-current motors. A series of tests was run and it was finally decided that for city work, for which the system was then laid out, the motor could not compete with the direct-current motor. It was decided, however, that such a type of motor would probably furnish the solution of the heavy railroad problem, but as there was no such heavy railroad problem at that time, the work was dropped for a while. But in 1897 the question of the use of the commutator type of alternating-current motor was again taken up—this time on a somewhat larger scale. Motors of 50 h.p. were built for variable-speed work, and given a long series of tests. Then after sufficient experience had been obtained, the work was gradually carried to the larger sizes.

In 1900 and 1901, when the question of the polyphase traction in Europe was so extensively advertised, it became evident that there was actually a demand for an alternating-current railway system. It was therefore decided to continue the previous work with large motors of the commutator type, and two motors of 100 h.p. were designed and built. For these also, the frequency adopted was 2000 alternations per minute, or 16⅔ cycles per second. This fractional figure was primarily adopted on account of certain steam-engine conditions. It was recognized that an even frequency of 16 or 18 would have been practically as good.

In the earlier work, with the 10 h.p. motors at the low frequency, it was recognized that it would be absurd to put such a system on the market, as at that time even 25 cycles had not been adopted. The frequencies in common use were 50 or 60 and a drop to 16 cycles was considered prohibitive. In the latter work, as 25 cycles had come into general use, and 15 or 20 cycles

had been talked of and proposed by certain companies, it was considered that in view of their advantages for railway work such frequencies should be adopted. The motors were hence built for the above frequency. The results obtained with these large motors were so satisfactory that a contract was taken for a rather large road and the apparatus prepared. Knowing that news of this would soon be abroad, it was decided that the matter should be brought before the AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS, and a paper was presented on the 26th of September—two years ago—which the speaker believes was the first announcement of the application of the single-phase alternating current to railway motors. There was considerable discussion—mostly criticism—and it was generally considered by the engineering public that the weak point of the system was the commutation. At the present time, however, the speaker believes this is no longer considered as a serious point.

Previous to building the 100 h.p. motors considerable experience was had with the commutation of such motors. Besides a long series of tests, we had run 40 h.p. motors at practically full load on a 60-cycle system for nine months, day and night. At the end of the nine months the commutators were in practically as good condition as in the beginning, showing that the commutator on such machines could be made to have a long life. The conditions of the 60-cycle machines were much worse than on the lower frequency, and the nine months of operation under the condition of steady service probably equalled two or three years of traction service; but the commutator stood up so well that we decided definitely that there was no difficulty on that point.

The principal reasons which led to the adoption of the single-phase motor were stated in the paper above referred to, and were that but one trolley wire would be required and that the motors had the series characteristics. It was considered that no motor, except one of the commutator type, would give suitable characteristics for the service, and it was stated that there were several types of motors, with commutators, which had the proper characteristics. All of these may be classed as series motors, although some of them are combined with transformers and may be considered as transformer series motors, or, under another name, as repulsion motors, and others are pure series motors. The pure series motor is one which can operate on direct current as well as alternating current. The repulsion motor can be modified so as to operate on direct current, but as ordinarily arranged it is not as well adapted for this as the other type. It was recognized in the first undertakings with this system that the motor would probably be required to operate on direct current at times, and the fact that the pure series motor was primarily a direct-current motor of a first-class design was one of the reasons which led us toward the adoption of that type. As both theory and experience indicated that such

motors would probably be wound for 200 or 250 volts, it was recognized that the motors would probably have to be operated in series for direct current, and either in series or in parallel for alternating current as might be desired. The arrangement required for permitting operation on direct current as well as alternating are rather complicated, due to the fact that it is neceassry to switch from one system to the other in passing from the alternating to the direct current. We did not suppose that the electrical public would consent to such a combination, but since that time we have found that in some instances they do not object seriously to the increased complication.

At the time that the alternating-current system was brought out it was considered that the principal field would be in heavy railroad work, because this motor furnished what was considered a general solution of the railway problem; as the railroads would have their own terminals and their own rights of way, the system would be an alternating-current system throughout. At the present time, however, roads are being installed which operate primarily on alternating current, but at the terminals and where they pass through intervening towns they operate on direct current.

The direct-current motor has never been considered as entirely suitable for the heavy railroad problem, as usually but two speeds, and at most but three speeds can be obtained with four motors, the third speed increasing the complication considerably. With the alternating-current motor of the commutator type any speed can be obtained for locomotive work, because any pressure can be applied to the terminals of the motor. As soon as alternating current is used for motors, we at once have a ready means of pressure transformation. As on locomotives for large capacity the difficulty of handling the current is considered a very prominent one. it was considered that some form of pressure control which varied the pressure without opening the circuit would probably be the best one. One form of pressure control permissible is what is called the induction regulator. This regulator varies the pressure without opening the circuit. The relation of the primary and secondary windings with respect to each other is varied. This gives a means of varying the pressure to the motors and varying the speed of very large motors with no tendency to sparking at the controller. The only time the circuit is opened is at the end of the operation when cutting it off. Therefore it was considered as an important feature in the solution of the general railway problem.

The single-phase system is the one means presented at the present time as the solution of the heavy railway problem. It has all the advantages of the direct-current motor in the variable-speed characteristic, and has also the advantage possessed by alternating current in the ability to use any line pressure desired, and to vary the pressure applied to the motor

and thus vary the speed over any range desired. It also has the advantage of permitting a system of control that can be obtained without sparking.

In the adaptation of the alternating-current motor to direct-current service, two 250-volt motors can be connected in series for 500 volts; also in operating on alternating current the motors can be connected in series, if desired, or in parallel. There is a possibility of danger in operating two motors in series in this way on alternating current, or even on ordinary direct current. In ordinary direct-current practice the use of two motors in series for part of the service is common practice, but there is this difference between the direct-current equipment and the alternating-current equipment. In the direct current we have motors wound normally for 500 or 600 volts. When operating in series the motors are connected, two in series, each one receiving 250 volts. Therefore, if one motor should slip its wheels and take the full pressure of the pair, it would still be operating at its normal pressure. But with two 250-volt motors connected across a 500-volt circuit, we have a different condition. In case one motor should take the entire pressure, we should have 500 volts across a 250-volt motor. That condition was considered early, and in the Washington, Baltimore, Annapolis project, a description of which was given in the AMERICAN INSTITUTE paper read two years ago, we showed an arrangement by which this could be avoided. Balancing transformers were connected across the two motors in series. The balancing transformer was across the outside terminals, and a tap from the middle of the transformer was connected between the two motors. In this way equal pressure was supplied to the two motors in series, and the danger of a runaway was thus avoided. It is not yet determined how important this is, but the speaker believes that something like this will be found advisable for the operation of motors in series, esepecially where high-power motors are used on medium weight cars for high-speed service. Possibly with comparatively low speed, and with very heavy cars, there may not be the same tendency to slip. On the direct-current part of the road, of course, the balancing transformer could not have any effect; but as the direct current is usually a very small part of the service, this danger would be lessened, due to the proportionate time in service.

In the application of the motor to use on both alternating and direct current, we have found some special conditions which affect the arrangement of control. Take, for instance, a large road being installed between Cincinnati and Indianapolis, where it is intended to run on direct current at the terminals and alternating current on the rest of the line. The normal speed on the alternating current part of the line is so great that it would be prohibited in the towns, and it is found that to get the speed down to the desired rate in the city service on the direct-current portion of the road, it is necessary to con-

nect the four motors all in series, and thus no series-parallel arrangement can be used. Pure rheostatic control is therefore necessary in the city. On the suburban part, a switch is used to throw the current from direct to alternating, simply throwing the four motors in parallel, and taps are used on the lowering transformers to get a number of pressures. In that way we get the effect of series-parallel control and even better, by having more than two steps. On a long line it is possibly of no great advantage to have many steps, but as a rule the more steps there are, the easier is the service on the controlling apparatus, and the more running speeds are available.

With regard to the application of the system to locomotives, on the steam roads where the systems are not tied up with existing electric plants, it is probable that in time the railroads will adopt their own pressures, and possibly their own frequency. This may not be 25 cycles but may be somewhat lower. The speaker believes that the electrification of the steam road may be a controlling factor in the change from direct to alternating current in city service. If the large railroads with their own large power plants adopt alternating current throughout, then the towns lying along the roads will in time prabably adopt the same power system, and even the large cities will sooner or later adopt the same system. At the present time the railroads, as far as they have gone, have adopted direct current because the cities through which they pass or enter are using direct current. When the railroads make the big end of the project, however, then the cities will adopt what the railroads are using. When this comes about the direct-current railway systems in the cities will be superseded by the alternating.

C. V. DRYSDALE: At this late hour in the discussion, the speaker does not propose to take up your time very much, especially as he is afraid that very few of us over in England have had much experience on this important subject. The speaker should like, in the first place, to take this opportunity of congratulating you on this side of the water on having carried this important problem to such an extremely successful issue as has been recently shown in Balston and in other places. This subject has been worked on in several places, yet to America belongs the honor of having constructed the first line of any considerable length working on the single-phase system. The way in which it has been done is admirable, when we remember that the result has been achieved by getting over the great difficulties that stood in the way of the series motor, and that in so doing it has been found practicable to use the same motive plants on direct- and alternating-current lines. That, in itself, is an enormous advantage over and above that of being able to use the single-phase alternating current.

It would be impossible for anyone to criticize any of the statements that have been made this morning, because they

come from gentlemen who have had such exceedingly minute experience in the special branch of the subject, that their remarks must be taken as gospel, at any rate for the present.

The speakers object in taking part in the discussion is rather to bring the matter back to first principles. This subject has been worked upon in many different ways and although the laminated series motor seems to have been the first to give us results will probably explain and solve the problem, yet there are some interesting questions as to whether there are any other ways of fulfilling the problem which may have other advantages. There is one thing that does not seem always to be kept in view in traction matters, in the starting of the cars, and that is the very simple matter that in the starting of the car you do not require power, you require force; if you wish to get anything into motion, what you require in the first instance is purely force, and until the body moves, it does not require power at all. One of the great advantages which the steam-engine has over any electrical system up to the present time, is the fact that when you first turn the steam into the locomotive you get the pressure on the back of the cylinder and get the starting force without taking any power from the steam. If it were not for the other disadvantages of the locomotive, there is no question that that one point would give it a strong pull over anything we have electrical, because if we turn to the ordinary direct current motor, we find that we have to use half, or with one motor, the whole, of the full-load power merely to secure a starting torque. This has several objections. Not only is this uneconomical and wasteful of power, but it throws a sudden strain on the general plant, and furthermore has to be wasted in resistances, and these resistances sometimes attain a considerable magnitude. With alternating-current motors these matters are worse, as we have in addition low power-factors and consequently difficulties in regulation.

The time is too short to refer to many other systems, but the speaker will mention one, that known as the Ward Leonard system, which at first sight appears to be an unworkable one. In the Ward Leonard system, as the speaker understands it, the system is to use a single-phase motor coupled to a direct-current generator which runs direct current on the locomotive or cars. Of course, the indirectness of the method seems to put it at fault, but on the continent that method has been developed with considerable hope of success, in fact with considerable practical success; and it has this great advantage that by the use of this arrangement you can start—get your starting effort—with very small power taken from your station. In the other system—it is too well known to be described here—you have your single-phase motor continuously running, and you can do the whole of the regulation of your speed, etc., by merely regulating the excitation of the generator. The result is that it is possible to get the full starting effort with only

something like one-third or one-quarter of the full-load current on the motors. That is so important a matter, especially in view of the huge trains liable to be thrown on the plant in the large schemes which we are hoping to see realized in the future, that we should give that method the consideration which it deserves, although it at first sight appears to be roundabout. In addition to that, we have the magnificent system invented by your President, Mr. Arnold, and the speaker hopes we shall hear more of that in the future. The speaker's only object in rising was to ask that we should hear as much about these systems as possible.

PRESIDENT ARNOLD:—The speaker is pleased to be put down as one of the speakers on this subject, but Messrs. Steinmetz and Lamme have so thoroughly covered the subject, and Dr. Drysdale has so kindly referred to the other systems known to most of you, that it is not necessary to say much more, particularly as the time is growing short.

One statement by Mr. Lamme, rather puts the speaker on the defensive. The speaker understood him to state that his announcement of the single-phase motor made in September 1902 was the first announcement of a single-phase system. In the month of June preceding, the speaker read a paper on a single-phase railway, known as the Lansing, St. Johns & St. Louis Railway, which was built at that time and which has since been put in operation. The speaker does not think it is just for the statement to be placed on record just in the manner in which it was made. Perhaps Mr. Lamme meant to say that his paper was the first formal paper on the subject, but the speaker's road was built and almost ready to operate at the time that he made his announcement.

F. J. SPRAGUE: The subject on the card is how best to use the alternating current in railway motors. It is largely a technical question. The alternating current motor is like a somewhat brilliant boy, who being exposed to various diseases has contracted a number of them; he has had a moderate experience in mumps and measles, and a touch of typhoid fever, and the various doctors, many able ones here and elsewhere, have administered, sometimes in homeopathic but oftentimes in allopathic doses, large measures of quinin and other drugs. Whether, as the child grows—and we are all hopeful of that child—and he is subjected to the various climatic conditions of commercial introduction and use, those undercurrents of disease common to all fevers will recur, or whether the child will outlive them and become strong and robust is a matter which must be left to future developments.

There is a larger problem. It is perhaps a more popular one, but of vital interest to us as engineers who are called upon to advise managers and others as to their financial expenditures, and that is: will electricity be used on trunk lines? Our worthy President, with whom the speaker has the honor to

be associated on some important work in that line, is very hopeful, and so is the speaker. But what are the reasons which may dictate the adoption of electricity on trunk lines? Will it be because an economical service cannot be gotten by steam? No. Will it be because there cannot be obtained to-day an efficient service? Again, no. Will it be because of aesthetic reasons? Distinctly not. If electricity be adopted on any trunk line service it will be because of the hard and fast rule of financial necessity, not because we engineers urge it. It will be because the men who raise the money, run the road and have to provide dividends find that it is the best way to do it, and the reasons which will apply to one road are not necessarily those which will apply to another. It is the speaker's belief that some of the largest expenditures, and those most fruitful of return to those who own the steam railroads of the country to-day will be for the purchase and control of competing electric railways which, having in the past acquired franchises of undoubted value which cannot be duplicated, have built up a profitable business which they can hold and which will increase. Many a steam railway will be better off financially and get bigger returns if it gathers in these franchises and systems, and operates its whole property with proper regard to the needs and capacities of each division than by electrification of its main lines, at least for a long time to come.

ELIHU THOMSON: It is certainly a pleasure to listen to a discussion of this kind in a joint meeting of the Institution of Electrical Engineers of Great Britain and the AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS, and the members of the Congress taking part. It is gratifying to find that there is so little dissent from the statements which have been made as to the future of alternating-current traction. Many of you will recall, no doubt, that at one time the electrical profession might have been said to have been divided into two camps, the alternating-current camp and the direct-current camp. The gentleman who preceded me was probably at that time more to be found in the direct-current camp than any other. The other gentlemen who have preceded me were to be found in the alternating-current camp. It is a fact, however, and those who have visited the power stations on the circular tour have noticed that the direct-current men have called in the alternating current to help them out, and combine, therefore, the virtues of the alternating current with the virtues of the direct current.

In the early days the speaker was connected and is still connected, with an organization which had not many prejudices of one kind or another. We had direct current, we had constant current series arc lights, constant-potential direct-current systems, and when the alternating current came we were ready to take that up without prejudice, and find out what there was in it.

In 1886 we put out our original alternating-current apparatus, and finding that the necessity might perhaps arise for motors on the system, it was at that time the speaker undertook to get a motor for that system, a self-starting alternating-current motor, and the first motor of the repulsion type was made in 1886 and finished in the fall of that year. It was a little affair and was found not to operate very well on the higher frequencies, but by connecting it to a machine, which the speaker was using for electric welding, giving 30 cycles, the speaker found it operated very well and satisfied him as to the general features of the machine. That machine, unfortunately, was sent to an exposition and lost. The Paris Exposition of 1889 had a couple of examples of machines on a little different basis. One of them, the speaker believes, is in England, at the Royal Institution, and another we have at Lynn. It was a machine which was started as a series alternating-current motor, and as soon as it reached a certain speed the commutator was short-circuited and it became an induction motor. It combined, therefore, the elements of both, but the design of such machines in those days was poor. We did not have even the distributed winding; we did not have the arrangements and the proportioning which we have to-day; nevertheless those little motors would give a half horse power for a moderate sized motor on 125 cycles, which was the highest frequency used. The speaker merely mentions these items as matters of history touching on the discussion. They have nothing to do with the discussion as to the different methods and systems of using alternating current in electric railway motors, but the speaker is a strong believer in the field being open for such work. He believes that not only will the direct-current motor maintain its place, but that certain lines of service which the direct-current motor cannot easily take will undoubtedly be taken by the alternating-current motor for railway service, and the exhibition of a system, which you have been able to see in use, and which adapts itself to the use of both currents, is certainly a very instructive one.

PRESIDENT ARNOLD: It occurs to the speaker that he may not have put his explanation in regard to Mr. Lamme's statement in just the way it should be put. The speaker thinks what he meant was that his announcement was the first of a purely single-phase commutator motor system. The speaker thinks with this correction Mr. Lamme will accept his statement. He has not sent the speaker any word, but this additional statement is due him. The speaker thinks his work was first, but Mr. Lamme got in with his announcement in September regarding the single-phase commutator motor.

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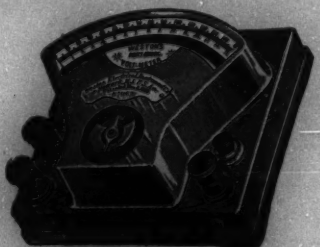

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	PAGE.
Allis-Chalmers Co.	xi
Allen, W. H.	xii
American Bell Telephone Co.	xvi
Arnold, Bion J.	xii
Baker & Co., W. E.	xii
Barstow, W. S.	xii
Bishop Gutta Percha Co.	vi
Brown Corliss Engine Co.	xix
Byllesby & Co., H. M.	xii
Calculagraph Co.	iv
Clarkson School of Technology	v
Clement, Edw. E.	xii
Corson, Wm. R. C.	xii
Cory, C. L.	xii
Cutler Hammer Mfg. Co.	xv
Cutter Co., The	Inside front cover
D. & W. Fuse Co.	vi
Electrical Testing Laboratories	viii
Electric Storage Battery Co.	i
Foote, Pierson & Co.	i
Fort Wayne Electric Works	xv
General Electric Co.	Inside back cover
Hooven, Owens, Rentschler Co.	xvii
Howson & Howson	xii
Jeffrey Mfg. Co., The	viii
Johns-Manville Co., H. W.	ii

	PAGE.
Krantz Mfg. Co., H.	x
Locke Insulator Mfg. Co.	xiv
Marine Engine & Machine Co.	vii
McIntosh, Seymour & Co.	i
Meridith, Wynn	xii
National Electric Co.	xviii
Osterberg, Max	xii
Polytechnic Institute of Brooklyn	v
Roebling's Sons Co., Jno. A.	Back cover
Sanderson & Porter	xiii
Sargent & Lundy	xiii
Schutte & Koerting Co.	x
Sprague Electric Co.	ii
Stanton, LeRoy W.	xiii
Stearns, Chas. K.	xiii
Stitt, Frederick S.	xiii
Syracuse University	v
Underhill, Chas. R.	xiii
VanNostrand Co., D.	iii
Western Electric Co.	viii
White & Co., J. G.	xiii
Westinghouse Electric & Mfg. Co.	xx
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Weston Electrical Instrument Co.	ii

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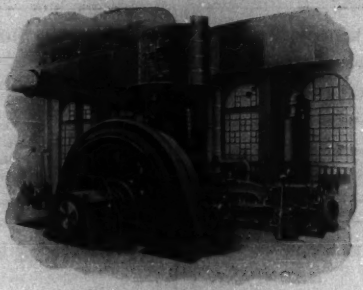

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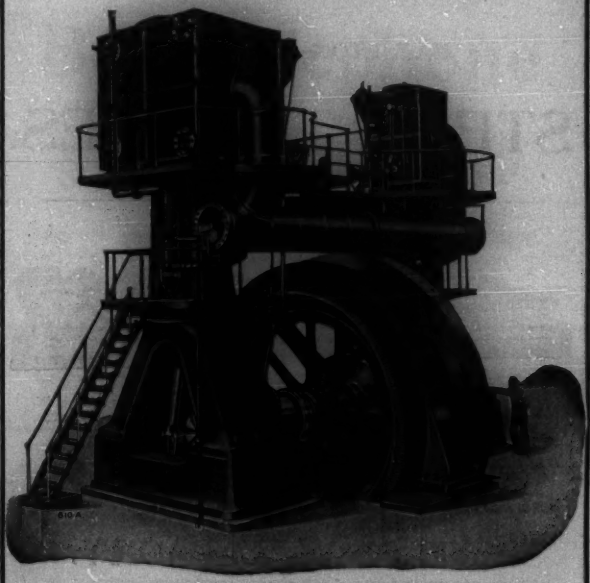

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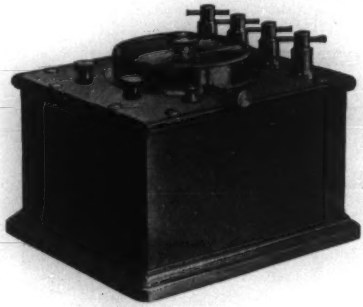

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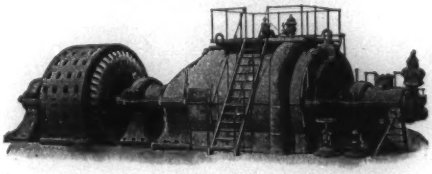

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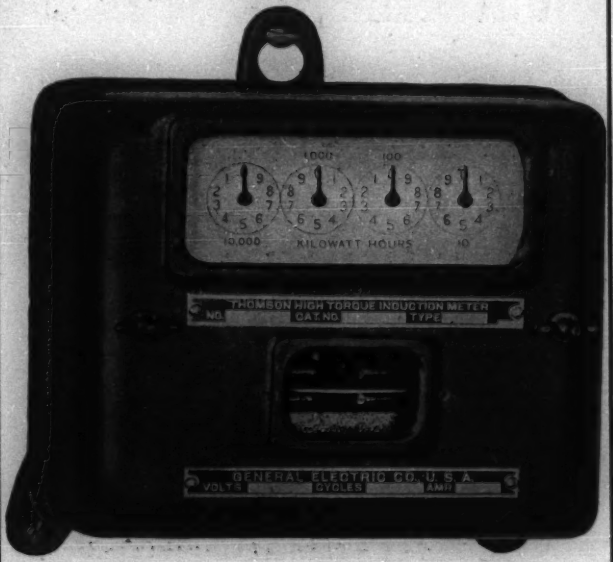

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